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FIFTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY MARCH 1-7, 2000

VOLUME 1

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INTRODUCTION

The 15th meeting of the U.S.-Japan Panel on Fire Research and Safety was held at the Southwest Research Institute in San Antonio Texas, March 1-7, 2000. Approximately 60 experts on fire science and fire safety engineering participated in the sessions. The core of the meeting consisted of technical sessions on materials performance and testing, people and fire, performance-based codes and standards, and fire suppression.

In addition, the meeting hosted a one-day Symposium in memory of Professor Howard W. Emmons of Harvard University who passed away on November 20, 1998. Professor Emmons was the father of modern fire science in the United States and had been an enthusiastic participant in these UJNR meetings. This was a celebratory event, with excellent technical papers, fond memories, and renewed friendships.

Among the technical sessions, the participants found time to visit the laboratories of the Southwest Research Institute and Omega Point Laboratories. The Saturday between sessions included a tour of the Johnson Space Flight Center in Houston and a re-enactment of the battle of the Alamo on its 164th anniversary. These provided further opportunity for the new participants in this venerable bi-national conference to spend time with those with extensive experience, and for the veterans to strengthen the fellowship of the international fire research community. Plans are now underway for a sequence of specialist workshops to be held in the years to come.

Agenda

Fifteenth Joint Panel Meeting of the
U.S. - Japan Panel on Fire Research and Safety

March 1-7, 2000
San Antonio, Texas

Wednesday, March 1, 2000 *(Opening ceremony and single technical session)*

8:30 Opening Ceremony: Jack Snell, Chair (NIST/BFRL)

9:30 Group Photo

Materials Performance and Testing

9:50 Ichiroh Nakaya (BRI): **"Japanese Progress and Overview of Building Material Performance and Testing"**

10:05 Takashi Kashiwagi (NIST/BFRL): **"Material Performance and Testing, U.S. Overview"**

10:20 Break

10:40 Masashi Yoshida (BRI): **"International Round Robin Testing With ISO 5660 Cone Calorimeter"**

11:00 Marc L. Janssens (SwRI): **"Balanced Approach to the Fire Performance Evaluation of Interior Finish Materials"**

11:20 Yuji Hasemi (Waseda Univ.) or Hayashi (BRI): **"Interpretation Of Small And Intermediate Scale Fire Testing"**

11:40 James G. Quintiere (U. MD): **"Formulas for Fire Growth Phenomena Based on Materials Properties"**

12:00 Lunch

1:00 Takashi Kashiwagi, Kathryn M. Butler, Jeffrey W. Gilman (NIST/BFRL): **"Fire Safe Materials Project at NIST"**

1:20 Thomas J. Ohlemiller (NIST/BFRL): **"Influence of Polymer Melt Behavior in Flammability"**

1:40 Tokiyoshi Yamada (NRIFD): **"Flammability Test for Flame Retardant Plastic Pallet"**

2:00 Richard E. Lyon (FAA): **"Heat Release Kinetics"**

2:20 Arthur F. Grand (Omega Point): **"A Study of the Effectiveness of Fire Resistant Durable Agents on Residential Siding Using the ICAL Apparatus"**

2:40 BREAK

3:00 Tour of SwRI Facilities

6:30 Welcome Reception – Menger

Thursday, March 2, 2000

People and Fire

9:00 John R. Hall (NFPA): **"Overview of Research on People and Fire in the U.S".**

9:15 Manabu Ebihara (Shimizu): **"Progress and Overview of Study on Evacuation Safety and Fire Risk Assessment in Japan"**

9:30 Richard G. Gann (NIST/BFRL): **"A Research Program to Determine When and How to Include Sublethal Effects of Smoke in Fire Safety Decisions"**

9:50 Yoshiro Yashiro (Shimizu): **"Fire Safety Design and Fire Risk Analysis in Consideration of Fire Progress Stage"**

10:10 Break

10:40 Ai Sekizawa (NRIFD): **"Development of Seismic-induced Fire Risk Assessment Method for a Building"**

11:00 Rita F. Fahy (NFPA): **"New Developments in EXIT89"**

11:20 Ichiro Hagiwara (BRI): **"Evaluation Method of Egress Safety"**

11:40 Lunch

Open Technical Session I

1:00 Takeyoshi Tanaka (Kyoto Univ.): **"Preliminary Model For Urban Fire Spread - Building Fire Behavior Under The Influence Of External Heat And Wind"**

1:20 Ken Matsuyama (Sci. Univ. Tokyo): **"Systematic Experiments Of Room And Corridor Smoke Filling For Use In Calibration Of Zone And CFD Fire Models"**

1:40 Koji Hayashi and Yoshihiko Kagiya (BRI): **"Research Project on Disaster Prevention in Town Planning"**

2:00 Morgan J. Hurley (SFPE): **"A Research Agenda for Fire Protection Engineering"**

2:20 Osami Sugawa (Sci. Univ. Tokyo): **"Flow Behavior Under Sloped Ceiling"**

2:40 BREAK

3:30 Depart for Omega Point Laboratories

4:00 Tour and dinner at Omega Point Laboratories

Friday, March 3, 2000

Performance-based Codes and Standards

9:15 Shuitsu Yusa (BRI) and Makoto Tsujimoto (Nagoya Univ.): **"Progress and Overview of Performance-based Codes and Standards in Japan"**

9:30 Craig Beyler (Hughes): **"Developments in PBD Technical Infrastructure: SFPE Engineering Design Guide and Engineering Practice Guides"**

9:50 Shuitsu Yusa (BRI): **"Outline of Reforming the Building Standard Law in Japan"**

10:10 BREAK

10:40 Yoshifumi Ohimya (BRI): **"Evaluation Method of Structural Fire Resistance"**

11:00 Takeyoshi Tanaka (Kyoto Univ.): **"A Risk-based Translation of Fire Resistance Requirement"**

11:20 Richard W. Bukowski (NIST/BFRL): **"Development of a Hazard-based Methods for Evaluating the Fire Safety of Passenger Trains"**

11:40 Naohiro Takeichi (BRI): **"Approach to Efficient System of Building Control"**

12:00 Lunch

Fire Suppression

1:00 Richard G. Gann (NIST/BFRL): **"Fire Suppression Research in the United States: An Overview"**

1:15 Naoshi Saito (NRIFD): **"Overview on Progress of Fire Extinguishing Research and Technology in Japan"**

1:30 William M. Pitts and Linda G. Blevins (NIST/BFRL): **"An Investigation of Extinguishment by Thermal Agents Using Detailed Chemical Kinetic Modeling of Opposed Jet Diffusion Flames"**

1:50 Anthony Hamins and Matthew Bundy (NIST/BFRL): **"Suppression of Low Strain Rate Flames by an Agent"**

2:10 T. Tsuruda (NRIFD) and D. Makarov (All-Russian RIFP): **"Numerical Modelling of Fire and Gaseous Fire Suppression"**

2:30 BREAK

3:00 Yoshio Ogawa (NRIFD): **"Fire Extinguishing Effect of Water Vapor"**

3:20 Masahiro Morita (Sci. Univ. Tokyo): **"Suppression Mechanism of Water Mist for Pool Fire"**

3:40 David T. Sheppard, Pravinray D. Gandhi (UL), and Richard M. Lueptow (NW Univ): **"Understanding Sprinkler Sprays: Trajectory Analysis"**

4:00 Hsiang-Cheng Kung (FM): **"Development of the Residential Sprinklers and Issues Highlighted by Recent Research"**

4:20 S. Noguchi, S. Ookubo (Yokohama R&D, Mitsubishi), and M. Miyasaka: **"Development of Pneumatic Atomizing Gun for Fire Fighting"**

Dinner on own

Saturday, March 4, 2000

Technical Outing - Johnson Space Flight Center (Houston)

Sunday, March 5, 2000

Free Day

Monday, March 6, 2000

Symposium in Memory of Professor Howard Emmons

9:00 Reminiscences

9:30 John L. de Ris (FM): **"Experiments Establishing the Similarity of Wall Fire Combustion"**

10:10 Takeyoshi Tanaka (Kyoto Univ.): **"Necessity of Design Methodology in the Framework of a Performance-Based Fire Safety Design System"**

10:50 BREAK

11:20 David D. Evans (NIST/BFRL): **"Use of Fire Simulation in Fire Safety Engineering and Fire Investigation"**

12:00 Lunch

Symposium in Memory of Professor Howard Emmons

1:00 Howard R. Baum (NIST/BFRL): **"A Convective Heat Transfer Model for Large Eddy Fire Simulations"**

1:40 Masahiro Morita (Sci. Univ. Tokyo): **"Mathematical Model for Fire Phenomenon"**

2:20 Craig Beyler (Hughes): **"Modeling Fire Growth in Room/Corner Configurations"**

3:00 BREAK

3:20 Arvind Atreya and David Everest (Univ. Michigan): **"Simultaneous Measurements of Drop Size and Velocity in Large-Scale Sprinkler Flows Using Laser-Induced Fluorescence"**

4:00 Yugi Hasemi (Waseda Univ.), Masashi Yoshida (BRI), and Ryosuke Takaike (NCC): **"Flame Length and Flame Heat Transfer Correlations in Ceiling Fires"**

4:40 Osami Sugawa (Sci. Univ Tokyo): **"Behavior of Flame/Plume Flow in and near Corner Fire - Entrainment Coefficient for Corner Fire"**

6:30 Symposium Banquet

Tuesday, March 7, 2000

Open Technical Session II

9:00 Steven T. Bushby (NIST/BFRL): **"Integrating Fire Systems with Other Building Automation and Control Systems"**

9:20 William L. Grosshandler (NIST/BFRL): **"Multi-function Sensing for Cybernetic Building Systems"**

9:40 Hiroshi Hayasaka (Hokkaido Univ.): **"Forest Fires in Boreal Forest - the Alaska Taiga"**

10:00 Patrick J. Pagni (Berkeley): **"Fire Spread by Brand Spotting"**

10:20 BREAK

10:50 Kazunori Harada (Kyoto Univ.): **"Revision of Zone Fire Model BRI2 for New Evaluation System"**

11:10 Long T. Phan (NIST/BFRL): **"Heating, Spalling Characteristics Residual Properties of High Performance Concrete"**

11:30 Tomohiro Naruse (BRI), Hasemi (Waseda Univ.): **"Wind Effect on Fire Behavior in Compartment"**

11:50 Lunch

Open Technical Session III

1:00 Yusaku Iwata (NRIFD), Hiroshi Koseki, and Marc Janssens(SwRI): **"Comparison of Combustion Characteristics of Crude oils using Cone Calorimeter"**

1:20 William M. Pitts and George W. Mulholland (NIST/BFRL): **"Improved Real-Scale Fire Measurements Having Meaningful Uncertainty Limits"**

1:40 Closing Session

LIST OF MEMBERS (JAPAN)
Who attended the 15th UJNR meeting

Dr. Hiroharu Habu (Japan Chairman)
Director General
Building Research Institute

Dr. Asamichi Kamei (Japan Vice-Chairman)
Director General
National Research Institute of Fire and Disaster

Dr. Ichiro Hagiwara (BRI Coordinator)
Head, Fire Safety Division
Building Research Institute

Dr. Ai Sekizawa (NRIFD Coordinator)
Chief, Third Research Division
National Research Institute of Fire and Disaster

Dr. Shuitsu Yusa
Associate Director for Fire Research
Building Research Institute

Dr. Ichiro Nakaya
Head, Fire Preventive Materials Division
Building Research Institute

Dr. Yoshihiko Hayashi
Head, Smoke Control Division
Building Research Institute

Dr. Tomohiro Naruse
Chief Researcher,
Evaluation System Division
Building Research Institute

Dr. Yoshifumi Ohmiya
Researcher,
Fire Preventive Materials Division
Building Research Institute

Mr. Masashi Yoshida
Chief Researcher, Fire Safety Division
Building Research Institute

Dr. Koji Kagiya
Researcher, Smoke Control Division
Building Research Institute

Mr. Naohiro Takeichi
Guest Researcher, Fire Safety Division
Building Research Institute

Dr. Naoshi Saito
Chief, Second Research Division
National Research Institute of Fire and Disaster

Dr. Tokiyoshi Yamada
Head, Special Fire Section
National Research Institute of Fire and Disaster

Dr. Takashi Tsuruda
Head, Second Extinguishing Section
National Research Institute of Fire and Disaster

Mr. Yoshio Ogawa
Research Staff, Second Extinguishing Section
National Research Institute of Fire and Disaster

Mr. Yusaku Iwata
Research Staff, Hazardous Materials Section
National Research Institute of Fire and Disaster

Prof. Yuji Hasemi
Department of Architecture
Waseda University

Prof. Makoto Tsujimoto
Department of Geotechnical &
Environmental Engineering
Nagoya University

Prof. Takeyoshi Tanaka
Disaster Prevention Research Institute
Kyoto University

Prof. Kazunori Harada
Department of Architecture
Kyoto University

Mr. Daisaku Nii
Student
Kyoto University

Mr. Keisuke Himoto
Student
Kyoto University

Prof. Masahiro Morita
Department of Applied Mathematics
Science University of Tokyo

Prof. Osami Sugawa
Research Institute for Science and
Technology
Science University of Tokyo

Mr. Ken Matsuyama
Assistant, Department of Architecture
Science University of Tokyo

Prof. Hiroshi Hayasaka
Department of Urban and Environmental
Engineering, Hokkaido University

Prof. Kenji Satoh
Department of Physics
Toho University

Dr. Yoshiro Yashiro
General Manager, Social Science
Department, Institute of Technology
Shimizu Corporation

Mr. Manabu Ebihara
Research Staff, Izumi Research Institute
Shimizu Corporation

Mr. Shintarou Noguchi
Research Staff, Yokohama Research &
Development Center
Mitsubishi Heavy Industries

LIST OF MEMBERS (U.S.)

Panel Members:

Dr. Jack Snell (U.S. Chairman)
Director, Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. Richard Gann (U.S. Coordinator)
Senior Research Scientist
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. Takashi Kashiwagi (U.S. Secretary)
Materials Fire Research Group
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. Ronald Alpert
Materials Research
Factory Mutual Research, Affiliate of FM Global

Dr. Howard Baum
Fire Dynamics Group
Fire Safety Engineering Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. Craig Beyler
Technical Director
Hughes Associates, Inc.

Dr. David Evans
Chief, Fire Safety Engineering Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. William Grosshandler
Chief, Fire Science Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. John R. Hall, Jr.
Assistant Vice President
Fire Analysis and Research
National Fire Protection Association

Dr. Anthony Hamins
Leader, Large Fire Research Group
Fire Safety Engineering Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. Marc Janssens
Manager, Materials Flammability Section
Department of Fire Technology
Division of Chemistry and Chemical Engineering
Southwest Research Institute

Prof. Patrick Pagni
Department of Mechanical Engineering
University of California-Berkeley

Prof. James Quintiere
Department of Fire Protection Engineering
University of Maryland

Associate Members

Prof. Arvind Atreya
Department of Mechanical Engineering and Applied Mechanics
University of Michigan

Mr. Richard Bukowski
Leader, Fire Safety Systems Group
Fire Safety Engineering Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Mr. Steven Bushby
Leader, Mechanical Systems and Controls Group
Building Environment Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. John de Ris
Materials Research
Factory Mutual Research, Affiliate of FM Global

Dr. Arthur Grand
Director of Research
Omega Point Laboratories

Dr. Rita Fahy
Fire Analysis and Research Division
National Fire Protection Association

Dr. Hsiang-Cheng Kung
Director, Fire Protection Research
Factory Mutual Research, Affiliate of FM Global

Dr. Richard Lyon
Manager, Fire Research Program
Fire Safety Section
Federal Aviation Administration Technical Center

Dr. Long Phan
Structures Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Dr. William Pitts
Leader, Advanced Fire Measurements Group
Fire Science Division
Building and Fire Research Laboratory
National Institute of Standards and Technology

Mr. David Sheppard
Large Scale Fire Research
Underwriters Laboratories, Inc.

15th Meeting of the U.JNR Panel on Fire Research and Safety
March 1-7, 2000
San Antonio, Texas
Session Chairs

Time	Session	U.S.	Japan
Wed; 3/1 a.m.	Opening	Snell	
Wed; 3/1 a.m.	Materials Performance and Testing I	Kashiwagi	
Wed; 3/1 p.m.	Materials Performance and Testing II		Nakaya
Thurs; 3/2 a.m.	People and Fire	Hall	Sekizawa
Thurs; 3/2 p.m.	Open Technical I	Hamins	Hagiwara
Fri; 3/3 a.m.	Performance-based Codes and Standards	Bukowski	Yusa
Fri; 3/3 p.m.	Fire Suppression	Alpert	Saito
Mon; 3/6 a.m.	Emmons Symposium I	Baum	
Mon; 3/6 p.m.	Emmons Symposium II		Hasemi
Tues; 3/7 a.m.	Open Technical II	Beyler	
Tues; 3/7 p.m.	Open Technical III		Yamada
Tues; 3/7 p.m.	Closing		Kamei
	Resolutions	Gann, Pagni	Saito, Sekizawa, Yusa, Hagiwara

MATERIALS PERFORMANCE AND TESTING

Japanese Progress and Overview of Building Material Performance and Testing

Ichiroh Nakaya
Building Research Institute
Ministry of Construction
Tatehara 1, Tsukuba-shi, Ibaraki 305-0802, Japan

ABSTRACT
In the field of fire safety research, the change of building regulation system from specification expressions to performance requirements is present worldwide trend. The author found that most of the available data are based on results of fundamental research. From the view on risk communication, research on the combustion of building material is insufficient. There has been a stronger demand for research on combustion of building materials. More research activities on this subject are most desirable.

1. Recent Progress in Japan
In these years, research on building material performance and testing has not been so active as that on fire safety design tools. In domestic conferences, several research groups reported their progresses. Seven papers appeared in the 1998 annual meeting of Japanese Association of Fire Safety Engineering. Twelve papers are appeared in the 1998 annual meeting of Architectural Institute of Japan. Seven papers appeared in the 1999 annual meeting of Japanese Association of Fire Safety Engineering. Four papers are appeared in the 1999 annual meeting of Architectural Institute of Japan.

Among these papers;
Five papers dealt with the fundamental flame spread phenomena,
Four papers dealt with the full scale and bench scale experimental results on flame spread phenomena,
Four papers dealt with the fundamental burning performance,
Three papers dealt with the small scale experimental results on burning characteristics of materials,
Ten papers dealt with the full scale or bench scale experimental results on burning behavior of materials,
Three papers dealt with the burning behavior of furniture.

Most of the research were done to get the input data to fire safety design system or verification of the system. This reflects the movement in Japan, which is the reform of the Japanese Building Standard Law to be performance based. Some of the research results will be presented in this session or the other.

2. Worldwide movement
Recently, CIB proposed two key program. They are "Performance Based Building Control" and "Sustainable Growth." The question was raised by the coordinator of CIB/W14 to its active members. It was what kind of new work item shall be launched in accordance with these new key program. The reaction from the members except a few was so cool that I felt strange. As I am deeply involved in both research program in BRI, I thought this kind of research is also active in the world.

In fact, "Performance Based Building Control" is the world wide slogan for the people engaged in building control. To activate the performance based building control system, various engineering tools to evaluate building performance are indispensable. Also industries now strongly recognize that it is very important to enable sustainable growth through the effort to reduce the load to environment. The progress in these area is most desirable.

But most of the active members of CIB/W14 are the professors of Universities and the researchers of

National Research Institutes. They are mainly doing fundamental research and may have small interface with building regulators or industry people. So they might not be interested in "Performance Based Building Control" nor "Sustainable Growth." Their main concern may be exchange of academic information on traditional scientific theme.

I experienced similar discussion at ISO/TC92 meeting. Now ISO/TC92 has a SC which deals with Fire Safety Engineering, which is SC4. SC4 recently published guidelines documents as ISO Technical Reports. SC4 people thought the speed toward the performance based building control will be boosted and the main job of standardization will become on those related with fire safety design. Through the discussion on new TC92 strategy, a new structure was proposed. The idea was the 4 SCs will be recomposed into new 2 SCs. One SC will in charge of the standardization of fire safety design methods. The other will be in charge of the standardization of measurement tools for the input parameters to the design system. This idea was appraised in SC4 but refused by the other SCs. Especially SC1(Reaction to Fire) and SC2(Fire Resistance) were strongly resisted the reform of the structure. SC3 was neutral but finally stand against the proposal.

I could learn something through these movement in two organizations. I felt the needs of Building Regulators and Industries might not been understood by the fundamental researchers or the testing organization people. Or they feel it is not necessary to respond such needs. This situation cannot be good but it comes to be real.

3. Hindrance to Performance Based Building Control

I have been involved in the reform of the Japanese Building Standard Law and related regulations. At the initial stage of this work, I was convinced that the research on combustion phenomena of solid fuel was fully advanced. If we could define the performance requirement clearly, we would find what physical properties shall be measured automatically. However, it was not so easy thing.

If changing the current expression of regulatory requirements composed of specification lists to performance expression, the work may be simple. But, without analysis to reveal what requirements are implied in the list of specification, the work cannot be completed and no change may be better than incomplete change since the range of choice is narrowed sometimes.

In case of the Japanese Building Standard Law, its main objective on fire safety can be interpreted to be safe egress in case of fire, prevention of collapse of the building after the fire and prevention of city fire. One of the main purpose of building material control may be to keep people in the building safe during egress. But to say what fire property control of material is necessary, we have to analyze the requirements carefully. The current expression of the requirement is based on the classification using test. So, first of all, we need to know what material performance is expected to be made clear. Many discussion had been done before the current test method was determined. Such as: What fire scenario is valid? What performance parameter shall be measured? But, unfortunately, there is little documents which report the discussion. Then we have to reduce the requirement from test apparatus and procedure.

The test methods currently used for building regulation are determined more than ten years ago. As the research on fire phenomena was not so advanced as now, they tried to represent a part of real fire phenomena in a small apparatus to observe material's reaction to fire instead of measuring fire property itself. This approach seems to be reasonable but it contains troublesome thing to proceed the reform process of regulation to be performance based.

It is desirable for the ideal structure of performance based regulation system to have layered requirements each of them are written in objective oriented. Most of the current regulation requires to

pass the test. This means that anyone cannot say fail or pass based on the test results obtained by another test method. If the regulatory requirement is written in objective oriented, we can easily define alternative solutions and it gives us big freedom of choice.

To make this dream real, I have tried to reduce what fire model was assumed and what performance would like to be verified. The detail information on pyrolysis process of solid fuel, heat release process by oxidation of flammable gas, emission of fuel gas from solid, etc. which are observed in real fire is indispensable to make this work completed. The research on combustion phenomena has greatly advanced in these years. But the information available are concentrated in those under ideal experimental conditions. This is not sufficient to reveal fire phenomena which was assumed when the current test method was defined.

If we introduce test methods to measure specified properties under simplified fire condition, this makes the test results to be suitable for common use but not to be suitable to understand what aspect of fire it is representing. Without close relation with real fire phenomena, the test results cannot appeal to satisfy regulatory requirement by the Building Standard Law. Then such kind of test methods cannot be used.

4. Fire Safety Concept

Why fire growth shall be prevented? How can we reduce fire damage to be minimum? The research on fire risk assessment has long history but the research to answer to these questions clearly is not popular. The most of people cannot understand the probability to experience fire damage. If they are told you may encounter fire in their life as same probability as or less probability than that of a traffic accident, they may understand what was told. Most of people want to know when the may experience fire and how big damage is expected.

I was asked to talk about fire rated materials at the seminar for consumer consultants. I thought the explanation of fire rating system would be good enough and went there without special preparation. Before the seminar, I talked with organizers and found that they were expecting me to talk how to distinguish fire rating of materials used in residences. Of course, I know what material is classified in what fire rating but it was hard to say what rating material was used in actual wall system. This experience make my view on fire safety changed.

Let's think about residential fire. In Japan, house wives spent the longest time in residence among her family. Most of wives would like to know how tough (non-ignitability or non-fire-spreadability) the material they see is and not on what class the material is rated. To make these people better knowledge on fire safety will contribute diminish the fire risk.

Recently, the word "Risk Information" became popular. This is reflecting the situation that people understand importance to transfer exact knowledge on risk to end user through the experience on nuclear plants' accidents and scandal on medicine. Researchers on risk reports that there is big difference in human reaction of to disaster between the people who understood the risk and those who did not understand it. If the people who was given exact information on risk fully and understood it well, they can behave themselves calmly. But if not, they behave themselves in panic.

This is also true in fire. In the work to reform the Building Standard Law to be performance based, relaxation of the requirement is done if it is reasonable. I am afraid the case where the requirement can be severe enough to give a certain safety factor and that give us great relief. In this case, the fire damage under unexpected condition can be too big if the safety factor was set small. Such a unexpected damage caused fire make people anxious and make the work for performance based regulation meaningless.

To avoid this situation, we have to define the risk clearly which the Building Standard Law is assuring. We have done the work to reform Building Standard Law taking care of this point. However, we encountered difficulty to explain clearly relationship between the essence of fire safety and the fundamental of the material combustion phenomena and could not attain excellent result.

5.Future work

In recent ISO/TC92 activity, the new future strategy has been discussed in addition to the future structure of the committee. Basic strategy is to supply International Standard quickly on demand of the customer. It was discussed in TC92 who is our customer. I believe our customer is the end user of the standards (consumer) who will get benefit finally and said so. But the direct users of the standards are industry, testing organization, regulators etc. Also consultant is new customer candidate.

Similar discussion was also done at the CIB/W14 meeting. It was reasonable that ISO/TC92 was raised as a customer of CIB/W14. But some said that the customer of CIB/W14 is the participant himself. Although this opinion may be reflecting the nature of CIB/W14, which is a researchers' forum, I believe engineer should do research which will fit to the social needs.

The needs of the research on material combustion phenomena is rising constantly. As I already pointed out, to understand fire phenomena exactly is important for fire safety assessment. Combustion characteristics of materials are important governing factor controlling this fire phenomena. Especially, combustion characteristics under real fire conditions such as heat release, heat transfer, flammable gas emission, generation of soot and toxic species, thermal deformation of solid fuel, etc. The real scale experiment is most desirable to study burning characteristics intensively. As this is not easy, we had better define several fire scenario and the model at first. Then burning behavior should be studied intensively under these fire scenario and model.

On the other hand, many computer model code has been developed. Recently, the importance of the verification and validation of them is strongly recognized. This is because the developer of the computer code and its user is not the same. The code can be used by the user in the way that the developer did not expect or without inspecting accuracy. To respond this new needs, the database for the verification of the computer code is desired.

Furthermore, the new demand of the society refused future use of halon. Nowadays halon replacement is a big issue. Many halogen compounds has been used as fire retardant. These chemicals block heat release process efficiently. But this means that it will produce halon and intermediate reaction product of oxidation process. These will increase soot generation and act as toxic species. At the development of new fire retardant, the fault point of halogen compound should be removed. From this view point, the development of the method to control flammable gas emission is most expected. For this purpose, the more intensive study on combustion phenomena of materials are indispensable.

At least, the systematic accumulation of the following four properties data are keenly necessary.

- Pyrolysis and charring rate of solid fuel which emits flammable gas with generating charring layer under constant heat flux.
- Pyrolysis rate of composite material.
- Flame shape and heat input profile to unburned fuel from flame.
- Individual process which is necessary to reveal the above phenomena.

Old research may give us some information. But more practical information on materials actually used in buildings should be corrected to make the model study applicable for actual building fire.

6. Summary

As I discussed, there is big demand in the research on combustion of materials. It is just to say that we, who are doing the research of material combustion, are standing on treasure island. Combustion of the material is one of the most important part of building fire. Correcting detailed data on this matter and putting them into database will make great contribution to wide spread of knowledge to control fire and improvement of building fire safety level.

Summaries of Technical Papers of Annual Meeting, JAFSE(1998)

1. Effect of Radiation on Flame Spread over Paper Sheets Containing Ammonium Phosphate, M.Suzuki et al.
2. Characteristics of Pyrolysis of Cellulose Sheets Permeated with an Adhesive, L.Gao et al.
3. Properties of Pyrolysis Zone in Downward Flame Spread over a Thin Paper with Opposed Flow, K.Sato and Y.Sakai.
4. Effects of Inert Gas and Water Vapor on Flame Spread over Paper, T.Danbara and N.Saito.
5. Combustion Characteristics of Wood and Fire Phenomena Observed in Small Compartment Fires, Y.Kudou et al.
6. Experimental Study on the Flame Spread beneath a Combustible Ceiling in a Room Configulation, T.Natori et al.
7. Comparison between Experimental and Simulation for Fire Spread on Lining Material, M.Matsudo et al.
8. Evaluation of the Combustibility of Interior Linings with the Revised Model Box Test, T,Kimura et al.

Summaries of Technical Papers of Annual Meeting, AIJ(1998)

9.A Study on Fire Spread behavior of Upholstered Funiture, H.Hayashi et al.
10. Experimental Study on Behavior of Chairs : Part 1, T.Mizuno et al.
11. Experimental Study on Behavior of Chairs : Part 2, H.Yamada et al.
12. Correlation of Gas Analysis Values between Toxicity Test and Model Box Test, S.Tasaka et al.
13. Evaluation of the Non-Combustibility of the Fire-Protecting Material Which Used ISO1182 Test Method, T.Goto and F.He
14. Burning Behavior of All-Weather Track in Athletic Field, S.Uehara and T.Nagaoka
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29. Various Characteristic Change of Woods or Construction Materials under Pyrolysis Condition, H.Hayasaka.
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MATERIAL PERFORMANCE AND TESTING
U.S. OVERVIEW

Takashi Kashiwagi
National Institute of Standards and Technology
Building and Fire Research Laboratory
Gaithersburg, MD, 20899

Marc L. Janssens
Southwest Research Institute
Department of Fire Technology
San Antonio, TX 78238

ABSTRACT

This paper provides an overview of activities pertaining to material performance and testing in the United States since the previous UJNR panel meeting on fire research. The first part of this paper focuses on recent materials related fire research activities. The second part focuses on testing of marine products for regulatory compliance, and on increased uses of the Cone Calorimeter.

MATERIAL PERFORMANCE

Although halogenated flame retarded materials are not an environmental issue yet in the U.S., continued concern in Europe and Japan about the potential formation of dioxin from the incineration of their spent end products is influencing U.S industry to seek alternative, non-halogenated flame retarded end products, in particular, for electronic components. A phosphorus based flame retardant approach is one of the most popular alternatives (metallic hydrates are others) but another new approaches are being explored. One of these is polymer-clay-nanocomposites which are polymers intercalated into the gallery spaces of layered nanosize silicate minerals to generate large interface areas between the silicates and the polymer. A reduction in heat release rate has been reported for various polymer resins with the use of appropriate organic treatments to compatiblize polymer resins and the silicate layers[1]. The flame retardant effectiveness is indicated by the fact that the addition of a mere 0.1 mass % of organically treated montmorillonite to polystyrene reduces peak heat release rate by about 40%[2]. However, the reduction in heat release rate tends not to be significant for further addition of clay beyond 3-5 mass %. It has been reported that the effect of the organic treatments on the clay surface on flammability properties of cyanate ester is complicated because one of four different treatments studied increased heat release rate over that of cyanate ester without any clay addition (the other three treatments significantly reduced heat release rate)[3]. Therefore, many studies are currently being conducted to determine the effects of the many parameters of clay-nanocomposites such as the type of clay, its organic treatment, intercalated vs. delaminated claylayers, molecular weight of polymer resin, and others on flammability properties. Another interesting, new FR approach is the enhanced formation of char to reduce heat release rate of polystyrene using Friedel-Crafts chemistry[4]. With the addition of a small amount (10%) of 2-

ethylhexydiphenylphosphate to a copolymer of styrene and 4-vinylbenzyl alcohol (10%), evidence of char formation was observed and the peak heat release rate was reduced by 60%.

The feasibility of a new measurement technique using mid-infrared (MIR) transmitting fibers coupled to a Fourier transmission infrared (FTIR) spectrometer to monitor changes in the condensed phase spectra of burning polymers was demonstrated[5]. The measurement is used to investigate thermally induced changes in polymeric materials during their burning. The fiber optic set-up used in the experiments consisted of a sapphire probe (300 μm in diameter and 10 cm in length) which was mounted on a steel rod and connected at both ends to zirconium fluoride (ZrF) cables. A reflectance spectrum results from the attenuation of the evanescent wave due to absorption by the polymer (and its degradation products) in the immediate vicinity of the probe as shown in Figure 1. The spectra obtained early in the cone calorimeter experiment (*i.e.*, before ignition) and in the vicinity of the peak heat release rate are compared to a spectrum of nylon-6 measured using a diamond reflectance probe at room temperature. This type of measurement for the sample with a flame retardant additive would be extremely useful to understand the FR mechanism. However, such measurement is much more useful if the technique is extended over the wider infrared range instead of the current mid-infrared range.

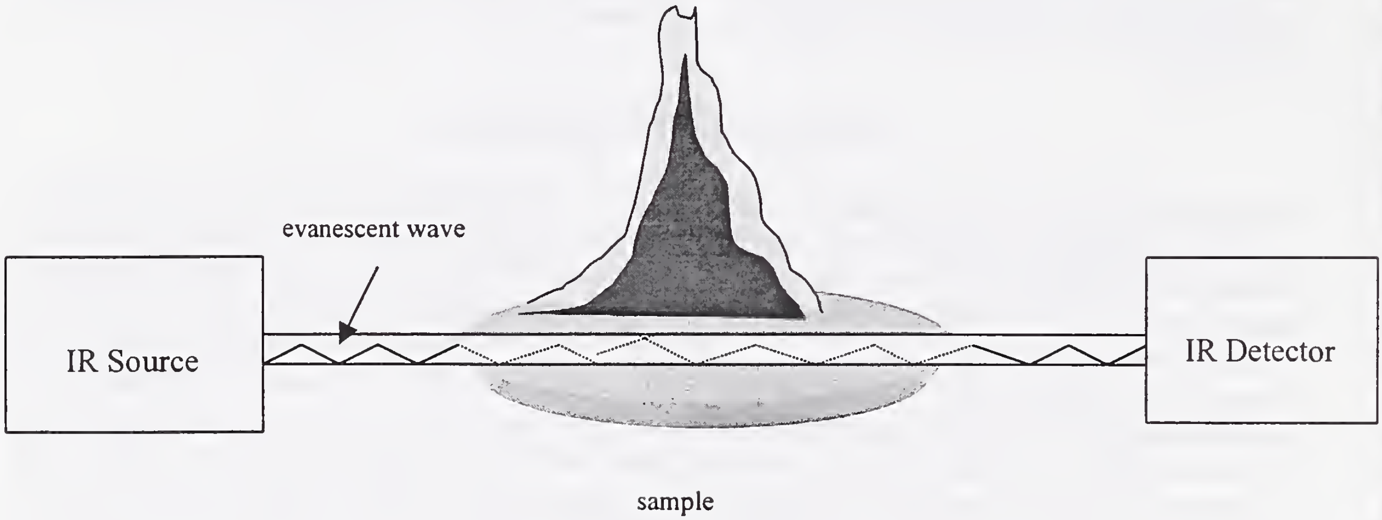

Figure 1. A schematic illustration of the real-time mid-infrared transmitting spectroscopic measurement of a sample during burning in the Cone Calorimeter.

An extensive materials fire research program has been conducted by Dr. Richard Lyon at the FAA Technology Center for application to fire safety of commercial aircraft interior materials. They have developed a unique device, a pyrolysis-combustion flow calorimeter (PCFC) to measure flammability parameters of milligram-sized research samples. This device consists of a high heating rate thermogravimetric analysis followed by complete oxidation of the degradation products with oxygen consumption measurement to calculate heat release rate. The validity of the measured heat release rate is demonstrated by the excellent correlation with those measured in the Cone Calorimeter as shown in Figure 2. This device is particularly useful for the

evaluation of new laboratory-produced polymers because the available amount of the experimental polymer is generally extremely limited. More detailed discussion of the device and the analysis is presented by Dr. Lyon in this meeting.

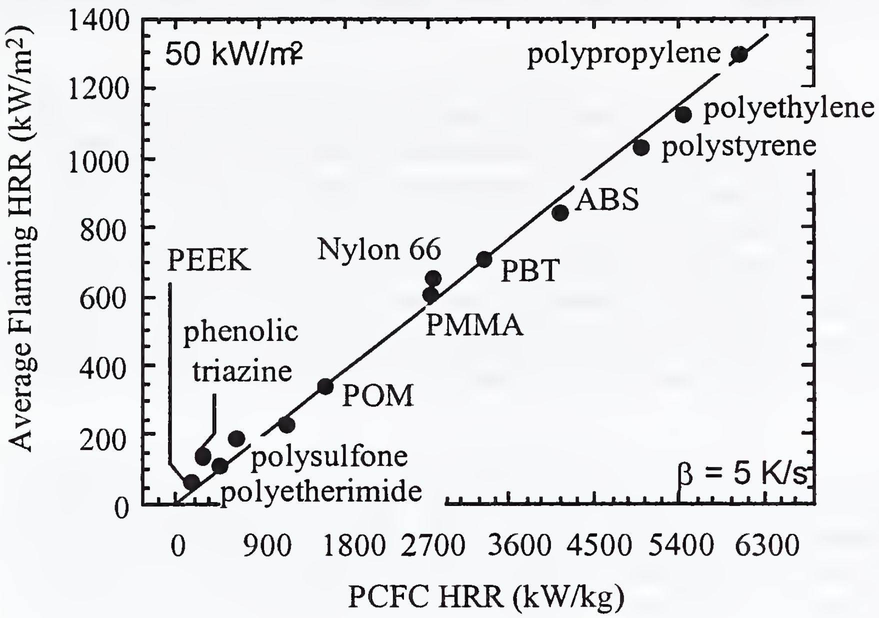

Figure 2. The relationship between heat release rate per unit mass measured in the Pyrolysis-Combustion-Flow-Calorimeter and average heat release rate per unit surface area measured in the Cone Calorimeter.

Another important, new research area, which has started recently at NIST, is a study of the effects of polymer melt flow on flammability properties of thermoplastics. When the heated surface is not horizontal (and in real applications it typically is not), the molten layer will have a tendency to flow downward; this can have a profound effect on the gasification and burning rate behavior since heat and, possibly, burning material are being transported. This phenomenon has been observed frequently in real fires but it has been almost completely ignored by the fire research community presumably because of its complexity. However, this is becoming more critical for understanding fire growth due to a significant increase in the daily use of thermoplastics, such as the commodity polymers. Dr. Ohlemiller presents his recent results in this meeting.

TESTING OF MARINE PRODUCTS

Since the 1998 UJNR panel meeting on fire research, testing and qualification requirements have changed considerably for materials and products that are used on ships that engage in international service. These requirements are specified in generic terms by the International Convention for Safety of Life at Sea (SOLAS). SOLAS is maintained by the International Maritime Organization (IMO), an agency within the United Nations that is headquartered in London, England.

Prior to July 1, 1998 each administration was permitted to implement the requirements using its own standard test methods and acceptance criteria. For example, the U.S. Coast Guard (USCG), which is the administration having jurisdiction (AHJ) in the United Sates, specified ASTM E 84 tunnel test criteria for interior finish materials. This test is widely used in North America, but not anywhere else in the world.

As of July 1, 1998 the IMO Fire Test Procedures Code (FTP Code) came into effect, and every administration throughout the world was required within six months to change its requirements and specify the universally accepted test procedures and acceptance criteria in the FTP Code. This had a very significant impact on material manufacturers and suppliers to the U.S. marine industry, because the old system was very different from and generally less stringent than that based on the FTP code. For example, interior finish materials are now regulated on the basis of the IMO surface flammability test, which is more severe than the ASTM E 84 test. In addition, interior finish materials may have to meet smoke and toxicity requirements that are very stringent as well.

Another important element of the new system is the requirement for manufacturers to participate in a follow-up program administered by a third party agency that is accredited by the administration to perform quality audits on a regular basis to ensure that the quality of a product is consistent. The follow-up requirement adds greatly to the cost of obtaining a type-approval certificate, and many manufacturers are reluctant to engage in a testing and follow-up program because of the expense.

The new rules have resulted in an increased activity of qualification testing for marine products. Some research is being conducted to improve products that met the old requirements, and that need to be upgraded to fulfill the new acceptance criteria. The use of intumescent coatings and wraps is often explored to address this problem.

INCREASED USE OF THE CONE CALORIMETER

On 1 January 1996, the High Speed Craft Code (HSC) entered into force as part of the Safety of Life at Sea (SOLAS) convention. This code deals with all aspects of the construction and operation of high speed craft. The most common type of ships that are regulated by the code are fast passenger and vehicle ferries that operate within 4 hours from the shore. The code permits that a high speed craft be constructed of combustible materials, provided certain fire performance criteria are met. Materials that meet these criteria are referred to as "fire restricting materials." The determination of fire restricting materials is based primarily on one of two tests. Bulkhead lining, and ceiling materials are tested using the ISO 9705 room corner test. Acceptance criteria for ISO 9705 are published in IMO resolution MSC.40(64) (MSC 64/22/Add.1, Annex 4). Furniture components (other than fabrics, upholstery, or bedding) and other components are tested using the ISO 5660 Cone Calorimeter. A research program was initiated by the USCG at SwRI in August of 1997. The primary objective of the program was to establish acceptance criteria to qualify materials as fire restricting based on performance in the Cone Calorimeter test ISO 5660. The proposed acceptance criteria that resulted from the research were presented at the

IMO Marine Safety Committee meeting in February of 1999, and were accepted in slightly modified form. Samples are tested in triplicate at a radiant heat flux of 50 kW/m^2 for a fixed duration of 20 min, in accordance with ISO 5660-1:1993 (time to ignition and heat release) and ASTM E 1354-97 (smoke production). The criteria for fire-restricting materials tested in the Cone Calorimeter are as follows:

- Time to ignition greater than 20 sec.
- Maximum 30-sec sliding average heat release rate does not exceed 60 kW/m^2.
- Total heat release does not exceed 20 MJ/m^2.
- Time average smoke production rate does not exceed 0.005 m^2/sec.

These criteria are now enforced to qualify fire restricting materials for use as components of furniture and other contents. Since they are consistent with the criteria for interior finish materials, they also provide a screening tool for materials that have to meet the ISO 9705 criteria. This is the first major use and application of the Cone Calorimeter for regulatory purposes.

Another area where the Cone Calorimeter is now used for regulatory purposes is rail transportation. The 1999 Edition of NFPA 30 specifies Cone Calorimeter criteria for interior materials of passenger rail cars, that can be used in lieu of the traditional requirements based on ASTM E 162, ASTM E 662, and other older test methods.

In the spring of 1997, seven companies and industry associations from the U.S. and Canada decided to sponsor a Cone Calorimeter interlaboratory test program. Reproducibility and repeatability were determined for the scalar variables measured in the Cone Calorimeter according to the protocol developed by the Board for the Coordination of the Model Codes (BCMC) The protocol specifies that samples be tested in the horizontal orientation in triplicate at 75 kW/m^2 for a fixed test duration of 15 min. The purpose of the project was to assist the model building code organizations, NFPA and various other groups in the development of a system to determine degrees of combustibility of building materials. Three U.S. and one Canadian laboratory agreed to conduct tests on sixteen materials. The results of this round robin show that the Cone Calorimeter, following the BCMC protocol, can provide precision similar to that cited in the current Cone Calorimeter standards. The findings from the round robin were submitted to a Task Group in ASTM, which is currently developing a standard based on the procedure that was used. This effort is paving the way for potential adoption of the Cone Calorimeter by the Building Codes.

Finally, at Southwest Research Institute we are seeing an increased interest in the use of the Cone Calorimeter as a predictive tool for other (typically larger scale) fire test procedures, such as the ASTM E 84 tunnel test, the NFPA 265/UBC 8-2 room test, and most recently the French Epiradiateur test. Sometimes, Cone Calorimeter data are used in conjunction with fire modeling. Tests are often supplemented with supplemental toxic gas analysis, using FTIR spectroscopy.

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INTERNATIONAL ROUND ROBIN TESTING WITH ISO5660 CONE CALORIMETER (INTERIM ANALYSIS REPORT)

Masashi Yoshida
Building Research Institute, Ministry of Construction

and

Yuji Hasemi
School of Science and Engineering, Waseda University

ABSTRACT

An interlaboratory trial has been carried out on the ISO5660 Cone Calorimeter by 19 laboratories from Asia-Oceania, American Continent and Europe as a CIB W14(Fire) subprogram. The project features cooperation of fire laboratories with only weak connection, and the methodology to improve reproducibility of reaction -to-fire tests among laboratories without strong face-to-face cooperation framework. The interim result of the analysis with the reported data suggest encouraging prospect to achieve a reasonable reproducibility by using common reference heat flux gage, and common calibration samples.

Keywords: Cone Calorimeter, round robin

INTRODUCTION

Introduction of the oxygen consumption principle and popularization of heat flux measurement in fire research during 1980's are among the most important changes in fire testing technologies. These have enabled practical and direct measurement of the most important index for fire hazard assessment and the direct index representing the intensity of fire exposure. These measurement technologies are a central vehicle to promote engineering approach in material fire safety through producing input data for fire models and evaluating the validity of fire models. Most of the recent ISO reaction-to-fire tests already adopt either the oxygen consumption principle or the heat flux measurement.

The oxygen consumption principle is, however, much more sophisticated than such conventional fire measurements as thermocouples or optical density. Also heat flux measurement using heat flux gage is believed to be sensitive to its maintenance and other conditions. There are many fire laboratories not very familiar with qualified use of these measurements, and it is believed that there are still many technical aspects left unsolved for the promotion of practical use and scientific application of these measurements. Many laboratories in Europe, and Northern America have already been involved in international interlaboratory calibrations partly in view of such problems[1].

Since around the beginning of 1990's, there has been significant spread of modern fire test methods and research-oriented fire test facilities to outside Western Europe and Northern America. This trend reflects the increase of fire risk through industrialization and that of the interest in fire safety science and engineering especially in newly industrialized countries. However, many of the new fire laboratories do not yet have direct access to international fire research and technical information, and there is still basic difficulty in the qualified use of modern fire tests in many of the new fire laboratories. In view of the recent increase of the Cone Calorimeters in Japan since around 1993, a round robin with the Cone Calorimeter was

initiated in 1994 under the coordination by Building Research Institute, Ministry of Construction, Japan. Several fire laboratories outside Japan joined this round robin as has been reported elsewhere[2]. There are, however, still many laboratories including CIB and CIB W14(Fire) members, who do not have a forum for this kind of activity. For further promotion of qualified use of heat release and heat flux measurement in such laboratories isolated from preceding laboratories or districts, it was felt necessary to develop some comprehensive procedure and possibly a network to improve reproducibility and establish confidence[3]. An extension of this interlaboratory cooperation was planned in order

- to include newer Cone Calorimeter users
- to ensure that there is a substantive number of laboratories especially in Japan and the newly industrialized districts intimately familiar with conducting tests in the Cone Calorimeter
- to enable recommendations and proposals to be made on the protocol set forth in the Cone Calorimeter standards and verify that these are consistent with operating experience
- to promote technical communication among fire laboratories in different regions.

This extended program was proposed as a CIB W14 sub-group programme, and was discussed at the CIB W14 Plenary meeting at Espoo, Finland, in January 1995. The objectives and scope of the interlaboratory trials are:

- to improve the skill and of fire growth measurements at fire laboratories, especially in newly industrialized countries and developing countries
- to further develop technical guidelines for fire growth measurements, especially for heat flux and rate of heat release
- to derive methods and protocols to improve reproducibility of heat release and heat flux measurement among fire laboratories
- to promote technical communication among fire laboratories in different regions.

This series of interlaboratory trials reflects the experience and lessons from the previous Cone Calorimeter interlaboratory trials[2], and has tried to adopt better defined procedures including use of reference heat flux gages calibrated against a single radiation source, use of single calibration sample and others.

Invitation for participation in the interlaboratory trials was first circulated to CIB W14 members in July, 1995 and the interlaboratory trials were started in November 1995. Non-CIB member laboratories who were interested in the participation were also invited to the program. 19 laboratories from 12 countries and districts finally participated in the Cone Calorimeter interlaboratory calibration. This paper intends to report the summary procedure of the program and the statistical analysis of the test data submitted in time.

INTERLABORATORY TRIALS

Participants

The 19 fire testing laboratories shown in Table 1 participated in the interlaboratory trials.

Table 1 Participating laboratories

Country/ District	Organization	Country/ District	Organization
Australia	●CSIRO Division of Building, Construction and Engineering	New Zealand	●Building Research Association of New Zealand
Canada	●Institute for Research in Construction, National Research Council	Poland	●Institute of Natural Fibres
China	●Institute of Building Fire Research, China Academy of Building Research ●State Key Laboratory of Fire Science, University of Science and Technology of China	Slovakia	●State Forest Products Research Institute
France	●Centre de Recherche et d'Etude sur les Procedes d'Ignifugation des Materiaux	Taiwan	●Architecture and Building Research Institute
Italy	●Central Institute for Building Industrialization and Technology, National Research Council ●L.S.F. Laboratorio di studi e ricerche sul fuoco	UK	●Department of Materials, Queen Mary and Westfield College, University of London
Japan	●Building Research Institute ●Forestry and Forest Products Research Institute ●Hokkaido Forest Products Research Institute ●Research Institute of Marine Engineering ●Japan Electric Cable Technology Center, Inc.	U.S.A.	●Forest Products Laboratory USDA- FS ●ATLAS Electric Devices Company

The participants will be identified only by alphabetical characters in this report. Dr.M.L.Janssens, then ISO/TC92/SC1/WG5 convener, Prof.M.Kokkala, CIB W14(Fire) Coordinator, Dr.V.Babrauskas, Prof. W.K.Chow and Dr.J.H.Fangrat served as advisers for this project.

Secretariat and Correspondence

Building Research Institute, Ministry of Construction, offered the secretariat. The role of the secretariat was to plan the project, to arrange specimens and instructions, and to make correspondence with participants. M.Yoshida made correspondence with Japanese participants, and A.Marchal, then STA Fellow at BRI, and Y.Hasemi, then BRI Head of Fire Safety Division, made correspondence with foreign participants.

Procedure

The interlaboratory trials were divided into the following stages:

1) Questionnaire on the apparatus

Questionnaire on the apparatus and its operation was sent to those who were interested in the participation(APPENDIX).

2) Calibration of heat flux gages

The project was initiated with the calibration of the heat flux gages of the participating laboratories with 11 reference Schmidt-Boelther gages which had been calibrated against a single radiation source. The heat flux gages were circulated in the participants, and each laboratory compared its heat flux gage for the determination of heat flux level with at least one reference heat flux gage. All reference heat flux gages returned to the secretariat were recalibrated. No notable difference from the initial calibration was found with each reference heat flux gage.

3) Calibration of heat release rate

Calibration of heat release rate was made with methanol. The tray was delivered from BRI to each participant. Choice of methanol as the common calibration specimen for heat release rate, in spite of the specification of the use of pure methane in the ISO5660 current draft, was because

- pure methane is difficult to obtain in many countries including some of the participating countries. Combustion heat of methane is generally so sensitive to its purity that its avoidance seemed to be reasonable to prevent confusion in the calibration.

- heat release rate of the methanol is comparable with that of most of the materials used as specimens of the present interlaboratory trials.

Although the secretariat offered diagnosis, relatively few laboratories reported the test result to the secretariat. Possible problems with heat release measurements at each participant were reported to the reporting laboratories for the improvement of the operations.

4) Preliminary round robin with a thick black PMMA specimen

Before dealing with different specimens, measurement of heat release rate for 25mm thick black cast PMMA was conducted for the diagnosis of the general performance of the machine of each participant. The black thick cast PMMA was chosen as a highly reproducible material whose properties are simple and combustion behavior is stable. Also black thermally thick PMMA is believed to be appropriate for the diagnosis on various aspects of burning behavior including time to ignition, heat release rate before the penetration of the specimen by thermal wave and total heat release rate. Three samples of black cast PMMA were sent to each laboratory. All the specimens were prepared using products from a single lot directly shipped by a manufacturer. Results and anticipated troubles of the apparatus of each laboratory was reported to each participant for the possible improvement of the operation and the apparatus.

5) Final round robin

Round robin was conducted using 8 different materials as specimens. During the round robin, frequent communication and information exchange was conducted between the secretariat and participants and sometimes among participants. Because of this active interaction, it is believed that detail of the operation at most of the participants was renewed and improved frequently. This may make the analysis of the data rather difficult, but such communication should have been quite effective for the improvement of measurement skill of laboratories which are otherwise isolated from international technical information on testing.

Specimens

During the last stage of the interlaboratory trials, the following materials prepared for the testing were chosen as specimens.

A)PMMA sheet, transparent, 10mm thick, density 1180kg/m^3(to be abbreviated as PMMA)
B)Medium Density Fiber Board, untreated(natural wood color), 12mm thick(MDF)
C)Polyvinyl Chloride Coated Steel Plate, black, 0.6mm thick, average density 6870 kg/m^3 (VCSP)
D)Gypsum board, covered by paper sheets on both sides, 9.5mm thick(GB)
E)Fiberglass-reinforced Polyisocyanulate(FGPC)
F)Polystyrene Foam(PS)
G)Polyurethane Foam(PU)
H)Fire Retardant Wood(FRW)

These specimens cover most types of combustible materials common in construction in the light of composition, dynamic combustion behavior and fire safety performance. PMMA was chosen as a representative noncharring stably-burning material, MDF was chosen as a wood-based industrial charring material, Polyvinyl chloride coated steel plate was to represent a thermally thin lined material with a sharp peak of heat release rate. Gypsum board with wall paper was to represent a thermally thick line material with a sharp peak of heat release rate. Gypsum board was chosen also to evaluate the quality and influence of conditioning of specimens as the fire performance of gypsum board is believed to be sensitive to the moisture. Fiberglass-reinforced polyisocyanulate, polystyrene foam and polyurethane foam were chosen to represent different burning behaviors of polymers. Although originally only the materials A) through D) were chosen and sent to the participants, analysis of the test results from the participants at this phase suggested that the problems anticipated at the preliminary round robin with black PMMA had not been well resolved. Also since some participants suggested needs of testing of foamed plastics, the secretariat arranged specimens of fiberglass reinforced polyisocyanulate, polystyrene foam, polyurethane foam and fire retardant wood and sent again to the participants. The materials A)～D) and E)～H) were tested at different period.

All specimens of each material were arranged by BRI using the products from a single lot directly shipped by the factory. 12 replicas of each material were sent to each participant.

TEST RESULTS AND COMMENTS

Table 2 is a summary of the test data delivery from participants. Although 19 laboratories participated, it was not able to open finally the data file from one laboratory. The table shows a summary for the rest of participants. Although most of the participants delivered data on the black PMMA, MDF, GB, PMMA, PS, PU and VCSP, relatively few participants reported data on methanol, and only one laboratory reported the data on FRW. The missing of the data on FRW at most of the laboratories is probably because the heat release rate from this material was too weak to measure.

Diagnosis with Black Thick PMMA

From previous round robins with the Cone Calorimeter and laboratory experiences, typical "symptoms" of test results can be summarized in conjunction with their possible causes as shown in Table 3.

Calibration of heat flux gages and heat release measurement with methanol conducted before the round robins actually aimed at preventing possible troubles with heat flux gages and oxygen analyzer among such common troubles with the Cone Calorimeter.

LAB.ID	BLACK PMMA	METHANOL -50	METHANOL -100	METHANOL -150	METHANOL -200	FGPC	FRW	GB	MDF	PMMA	PS	PU	VCSP
A	1	1	2	1	1	3		3	3	3	3	3	3
B	1	1	1	1	1	3	3	3	3	3	3	3	3
C	1					3		3	3	3	3	3	3
D	1					3		3	3	3	3	3	3
E	1					3		3	3	3	3	3	3
F	1	1	2	1	1	3		3	3	3	3	3	3
G	1					5		3	3	3	4	3	3
H	1	1	1	1	1	3		3	3	3	3	3	3
I	1					3		3	3	3	3	3	3
J	1							3	3	3			3
K	1					3		3		3	3	2	3
L	1					3		2	2	2	2	3	3
M	1	1	2	1	1	3		3		3	3		3
N						3		3	3	3	3	3	3
O	2												
P	2	1	2	1	1	6		3	3	3	3	3	3
Q	1					3		3	3	3	3	3	3
R	1								3	3			3

HEAT FLUX 30kW/m2 Test Number

LAB.ID	BLACK PMMA	FGPC	FRW	GB	MDF	PMMA	PS	PU	VCSP
A	1	3		3	3	3	3	3	3
B	1	3	3	3	3	3	3	3	3
C	1			3	3	3	3	3	3
D	1	6		6	3	3	3	3	3
E	1	3		3	3	4	3	3	3
F	1	3		3	3	3	3	3	3
G	1	5		6	3	3	3	3	6
H	1	6		3	3	3	3	3	3
I	2	3		3	3	3	3	3	3
J	1			3	3	3			3
K	1	3		3		3	3	3	3
L	2	3		3	3	3	3	3	3
M	1	3		3		3	3		3
N		3		3	3	2			2
O	1								
P	1	3		6	3	3	3	3	6
Q	1	3		3	3	3	3	3	3
R	1				3	3			3

Table 3 Typical troubles with Cone Calorimeter and Resulting Symptoms

	troubles	symptoms in indicated data			remarks
		time to ignition	peak heat release rate	total heat release rate	
Heat flux gage	indicated heat flux higher than reality	too long	too low		Heat flux gage of each laboratory was to be calibrated against common refe`rence heat flux gage.
Oxygen analyser	preset initial O_2 concentration higher than reality		too high	too high	Actual ambient O_2 concentration in laboratory can be fluctuated from default O_2 concentration.
Duct flow velocity	excessively high	too long	too low		Excessively high flow rate often causes convective cooling of the specimen surface.Excessively high flow rate often causes convective cooling of the specimen surface. This effect is believed to be more influencial to time to ignition than heat release rate.
Specimen holder	thermal insulation or substrate behind specimen		too high		Insulation behind specimen should not influence time to ignition nor heat release rate before the penetration of the specimen by thermal wave.
Preset area of burning surface	larger than reality		too low	too low	Preset value of surface area of each laboratory was reported to the secretariat.
A/D transform board	indicated time interval longer than reality			too high	
Data processing	smoothing		too low		

After the preliminary round robin with black thick PMMA, some analysis was was made on the submitted data for diagnosis of the apparatus of the participating laboratories. Figures 1(a) - (d) are a summary of the data on the heat flux level $50kW/m^2$. The alphabetical characters denote the participants. While the data are rather scattering in Figures 1(a)-(c), total heat release rate is clearly correlated positively with peak heat release rate. Positive correlation between peak and total heat release rates were also observed at the heat flux level $30kW/m^2$. This suggests a need of the calibration of oxygen analyzer, while the data do not show any sign for the inconsistency in the measurements of heat flux and duct flow. Diagnosis on the black thick PMMA data also revealed troubles of specific laboratories. For example, time to ignition reported from laboratory I was rather unstable in that the time to ignition for $50kW/m^2$ was very short and that for $30kW/m^2$ was very long. Through communication between the secretariat and the laboratory, this was finally attributed to the control of duct flow rate. The weak peak heat release rate at laboratory R was attributed, at least partly, to the smoothing of the test data. Signs for other troubles were recognized at each participant, which are summarized as:

Improper calibration of heat flux gage: F, K
Duct velocity: F, I, K
Wrong preset of burning surface area: A, C, P

Heat release rates on black PMMA reported from those laboratories that had joined the heat release calibration with methanol seem to be within narrow range around the average if data calculated with wrong surface area is properly adjusted. This is believed to endorse importance of the calibration of heat release rate using some appropriate material for the maintenance of Cone Calorimeter. Such information was delivered to each participant before the round robin with commoner building materials.

Final Round Robin Results

Figure 2 - 8 are summaries of the correlations for the materials used for the final round robin summarized in similar way with the preliminary round robin.

The peak and total heat release correlations for some of the specimens during the first phase of the round robin, e.g. gypsum board at 30kW/m^2 heat flux level(Figure 5(h)), indicate a sign for the diverse definition of the ambient O_2 concentration which had been already pointed out at the preliminary round robin. At most of the participating laboratories, gypsum board was the the specimen to start with at this stage of round robin. Weaker correlation between peak and total heat release for other materials, except for a few laboratories, suggests improvement of the operation of oxygen analyzer during this stage of the round robin. Reported total heat release on PMMA very consistent among the participants(Figure 2(d),(g)) seems to endorse the improvement of the oxygen analyzer before and during the round robin process. Results on the materials tested in the second phase, FGPC, PS, and PU, show only very weak correlation between the peak and total heat release.

The significant scattering of the data for gypsum board at 30kW/m^2 heat flux level(Figure 5(e),(g)) should be noteworthy. Performance of gypsum board, especially at weak heat flux level, is believed to be the most sensitive to moisture among the materials tested in this round robin. This scattering may indicate the diverse quality of conditioning among the laboratories.

Results on Polystyrene at 30kW/m^2 (Figure7(a)) are divided into two groups, one with higher heat release rate and shorter time to ignition and another characterized by very long time to ignition(laboratories A,I and N). This material causes surface melting and degradation prior to the ignition when it is exposed to relatively weak external heating. Such surface degradation is believed to decrease the incident heat flux to the surface and delay the ignition. Laboratories A and I are "slow" laboratories in the sense that time to ignition reported from them was generally longer than others. Results from these two laboratories far from others are attributed to the start of melting before the ignition.

From general observation of the time to ignition, it can be concluded that laboratories F and I are "slow" laboratories and E and K are "fast" laboratories. Time to ignition reported by laboratories E and F was sometimes very far from others, while peak heat release rate and total heat release rate reported from these laboratory are generally around the average of all participants. This suggests that laboratory E and F rely on different definitions of ignition from all other participants. Data on polystyrene at 30kW/m^2 from F fallen into the "faster" group(Figure 7(e), (g)) may support this explanation for the general features of the data from laboratory F. Time to ignition reported from laboratory E at the second phase(Figures 6, 7, 8) became somewhat closer to average than at the first phase. This may indicate conscious or unconscious change of the definition of ignition at this laboratory caused by the diagnosis on the results at the first phase. On the other hand, peak heat release rate from laboratory I was generally lower than others, which suggests the heat flux gage output of this laboratory higher than the reality. The duct flow velocity of this laboratory, estimated from its duct pressure

data, was found to be one of the lowest among the participant, which is believed to lead rather to faster ignition.

Lessons from the Interlaboratory Trials

This project revealed the importance of interlaboratory calibration of heat flux gages and heat release measurements and technical communication among laboratories for the reproducible operation of the Cone Calorimeter. Although there was significant scattering of the data at the beginning of the project, those laboratories active in the pre-roundrobin calibrations and communications with the secretariat throughout the project, such as C,D,G, and L, demonstrated consistent tests results during the final round robin although all these four laboratories are geographically isolated on the globe and are believed to have had few contact with each other before this project. Active correspondence is obviously a sign for the strong interest and the skill of the person in charge. The experience with this project also suggests importance of internal communication in laboratory. From communication between participants and the secretariat, it has been often felt that diagnosis of the test results and suggestions from the secretariat was not forwarded to those who actually operated the Cone Calorimeter. At some laboratories, it seemed that corresponding scientist ran the apparatus by himself/herself; such laboratories generally were able to improve the operation smoothly. Perhaps these will apply not only to the Cone Calorimeter but also to different types of modern fire tests and measurements. In that sense, interlaboratory cooperation is believed to be essential for the promotion of experimental fire research.

Acknowledgments

The coordinators of the round robin would like to acknowledge efforts of Dr.A.Marchal as a secretary during his stay at BRI, and technical support of Dr.M.L.Janssens, Southwest Research Institute, then ISO TC92/SC1/WG5 convener, who contributed valuable advices on the project and offered updated drafts of the ISO5660 Cone Calorimeter for this program.

This project has been helped by the generous contributions of numbers of organizations and individuals in various ways.

Participation of international experts in the international business meeting for the project in Tokyo, October 1995, was financially supported by the TOSTEM Foundation, Japan. Its meeting place was offered and arranged by the Association of International Communication for Building and Housing(currently International Institute for Buildings and Housing). Part of the specimens were offered by the Association of Fire Protective Materials Manufacturers. The Association and Architectural Institute of Japan offered arrangement of domestic working meetings. The stay of Dr.Marchal at Building Research Institute was essentially supported by the STA Fellowship through arrangement by Science and Technology Agency, JRDC and JISTEC. Prof.T.Wakamatsu, Science University of Tokyo and Building Center of Japan offered admiministrative assistance for the extension of his stay. The coordinators wish to acknowledge these supports which helped ensure the pursuance of the project.

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CONE CALORIMETER ROUND ROBIN PRELIMINARY QUESTIONNAIRE

Name of Laboratory:____

Manufacturer of your Cone Calorimeter: ______________________________

Product Name of your Cone Calorimeter: ______________________________

Manufacturer and Product Style(if available) of Heat Flux Gage:__________________

Cone/Specimen Environment:____

Please describe how many out of the four vertical sides of the Cone/specimen area are covered with permanent wall, glasses or doors.

____

____

Gas Analyzer:	Manufacturer	Product	Range(%)	Estimated Delay of Response(sec)
Oxygen				
Carbon Monoxide				
Carbon Dioxide				

Calculation of heat release rate(please tick)

- ☐ software prepared by the manufacturer, equations unknown
- ☐ software prepared by the manufacturer, equations known(please attach documents describing the equations if available)
- ☐ software prepared by ____________________(please attach the equations if possible)
- ☐ availability of smoothing(please attach the concept if available)

Treatment of the initial condition of O_2 concentration in the calculation of heat release rate

- ☐ assumed as 20.95%
- ☐ average for _____seconds until the start of the test

Laboratory conditions:

size of the room for the Cone Calorimeter: _______m^2

installation of air conditioning/forced ventilation etc:

☐ air conditioning during test(if yes, please note the approximate room temperature and humidity during tests)

☐ ventilation only

Maintenance:

Is your Cone Calorimeter run always by specific person(s)?

____

Is the heat flux gage used for your Cone Calorimeter calibrated periodically against any radiation source or virgin heat flux gage?

____

____

____

____

Conditioning of specimens:

Do you condition specimens for your Cone Calorimeter before each test? If so, please describe the temperature, relative humidity and the term for the conditioning.

____

____

____

____

Experience in the use of Cone Calorimeter:

In what year did your laboratory introduce the Cone Calorimeter equipment, and how long does your laboratory have used it?

____

How many times a year does your laboratory use the Cone Calorimeter equipment?

____

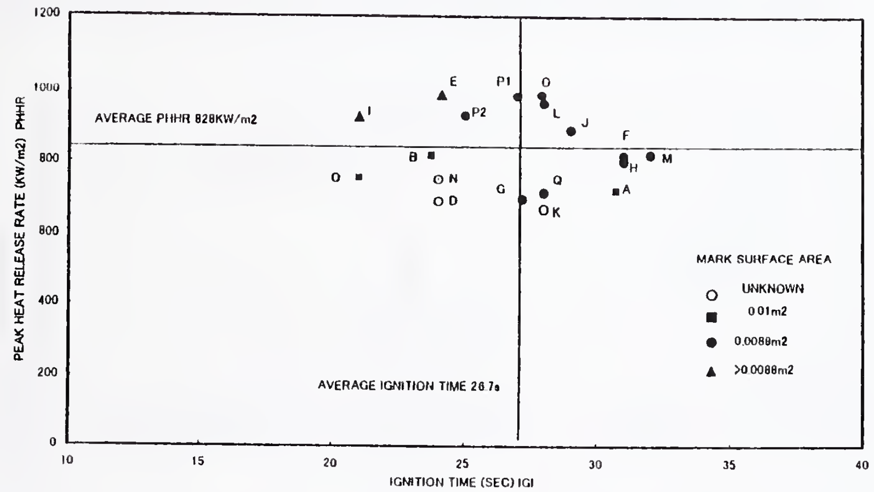


Figure 1(a) black PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m² (Preliminary round robin)

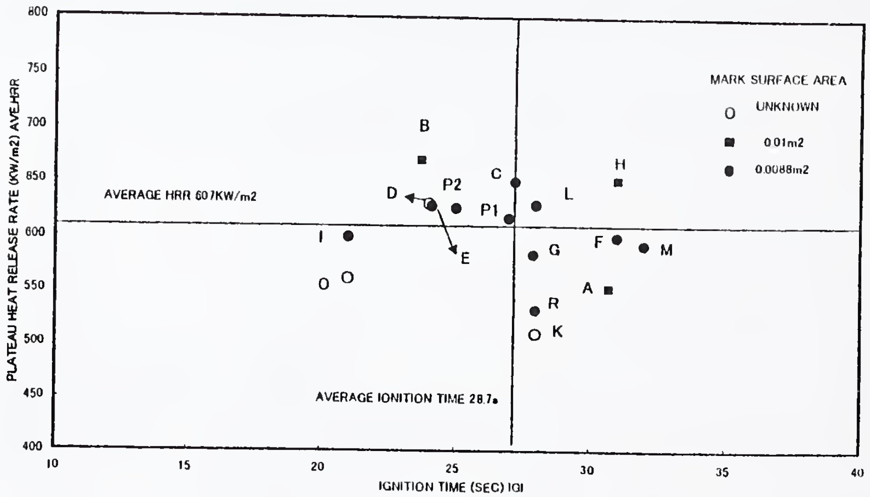


Figure 1(b) black PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m² (Preliminary round robin)

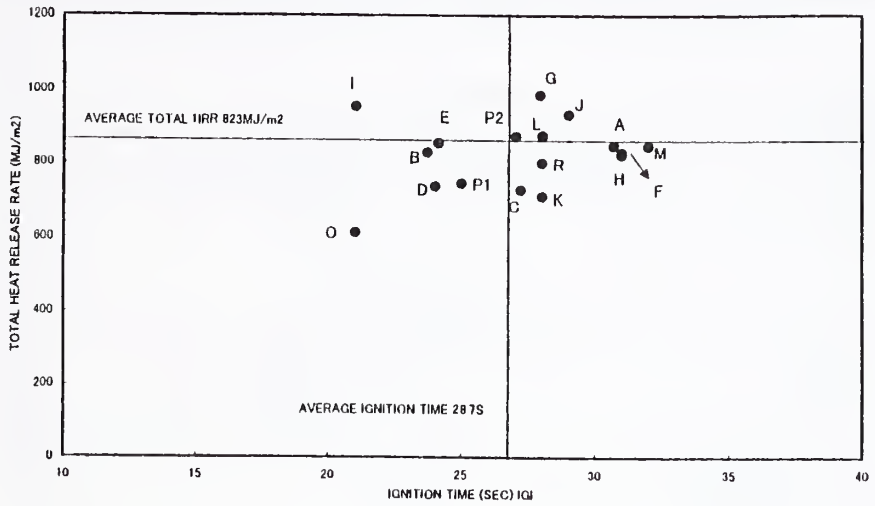
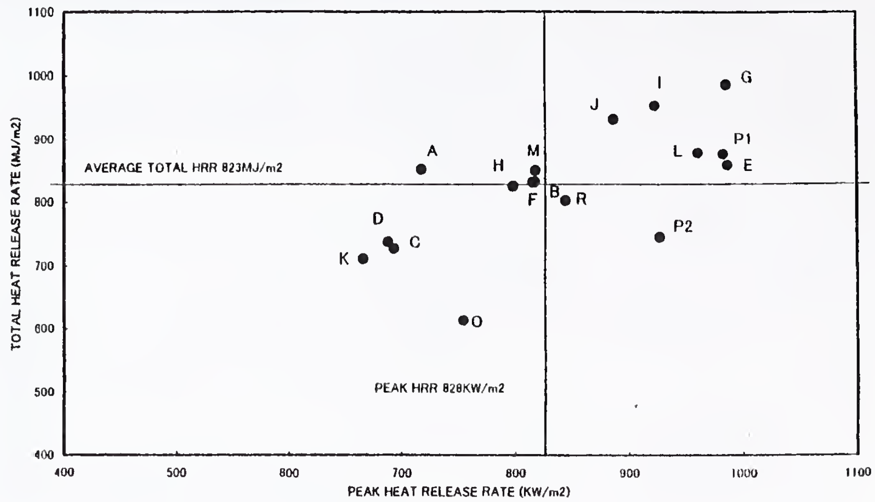


Figure 1(c) black PMMA, Time to ignition vs. Total heat release
Heat flux level: 50kW/m² (Preliminary round robin)



d
Figure 1(~~b~~) black PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m² (Preliminary round robin)

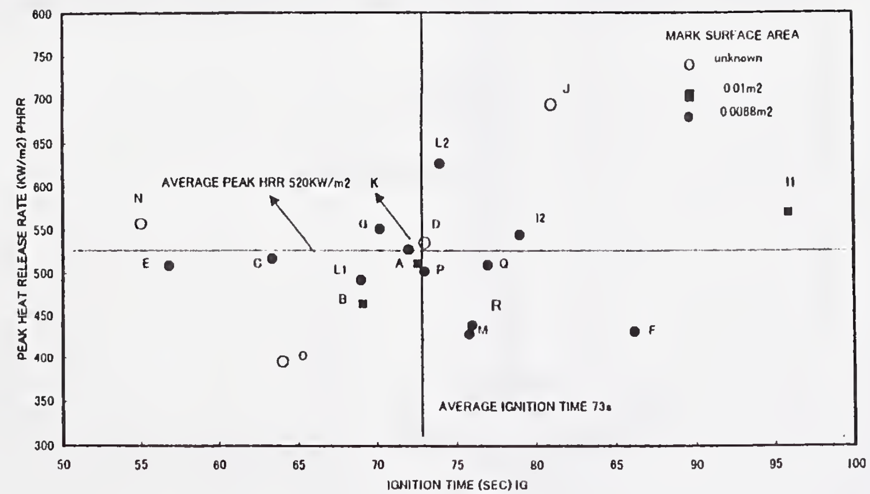


Figure 1(e) black PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m² (Preliminary round robin)

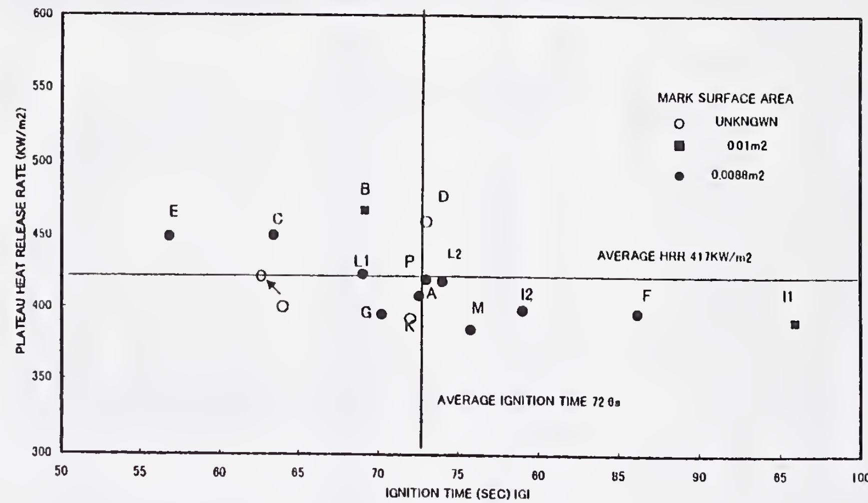


Figure 1(f) black PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m² (Preliminary round robin)

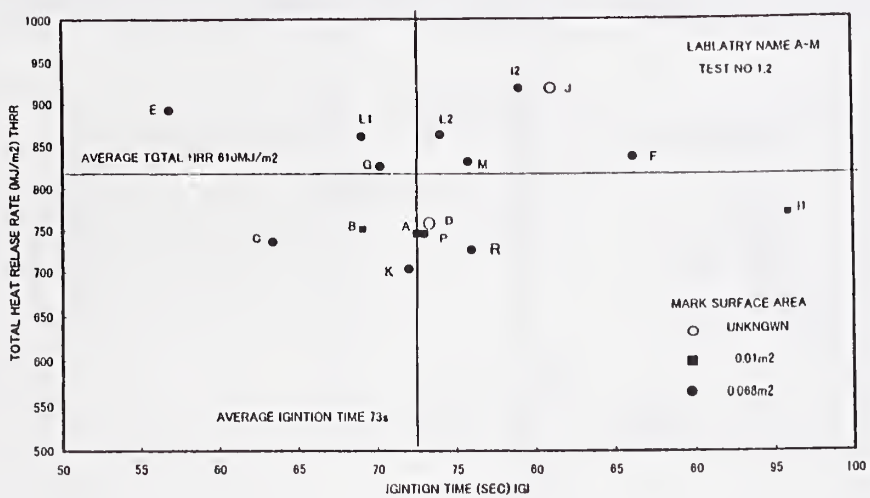


Figure 1(g) black PMMA, Time to ignition vs. Total heat release
Heat flux level: 30kW/m² (Preliminary round robin)

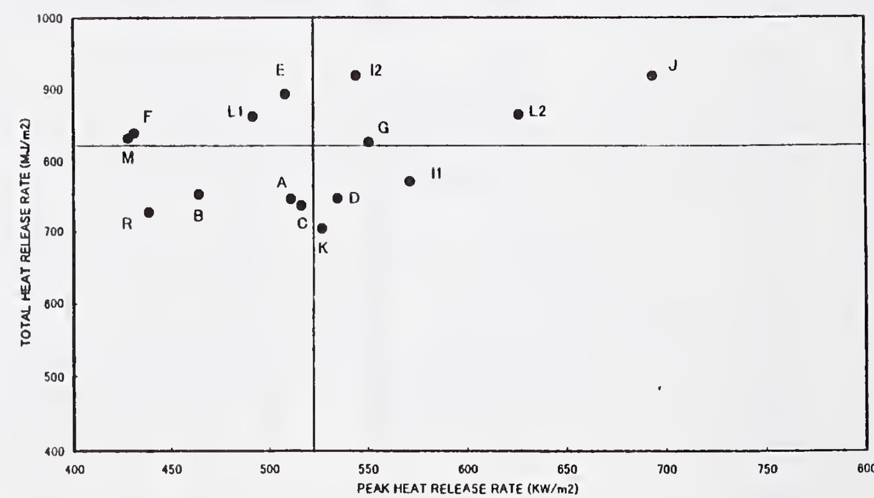


Figure 1(h) black PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m² (Preliminary round robin)

Figure 2(a) PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

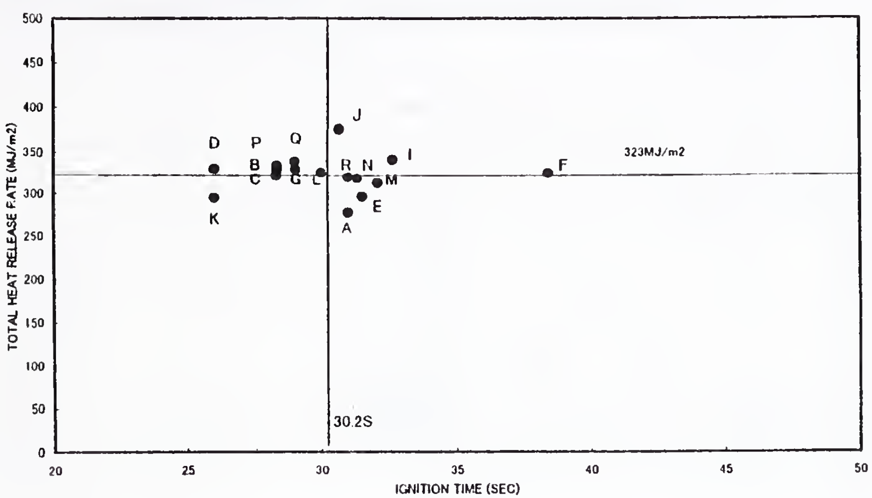


Figure 2(c) PMMA, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

Figure 2(b) PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

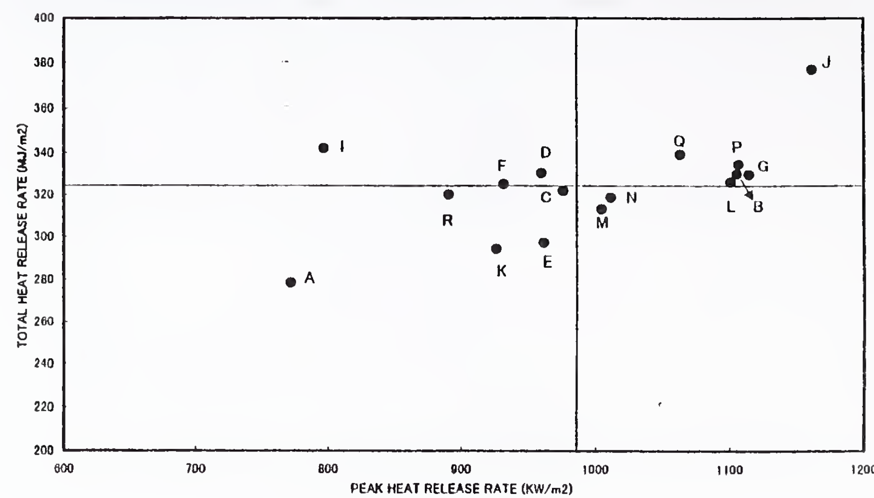


Figure 2(b) PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

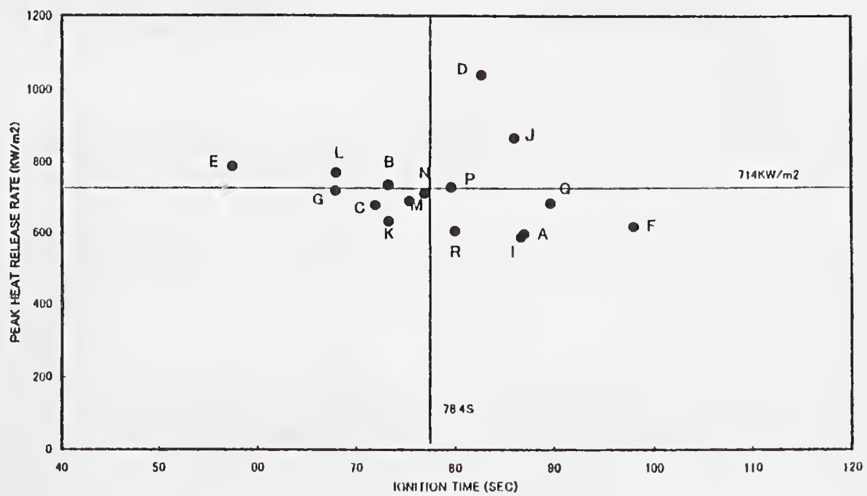


Figure 2(e) PMMA, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 2(f) PMMA, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

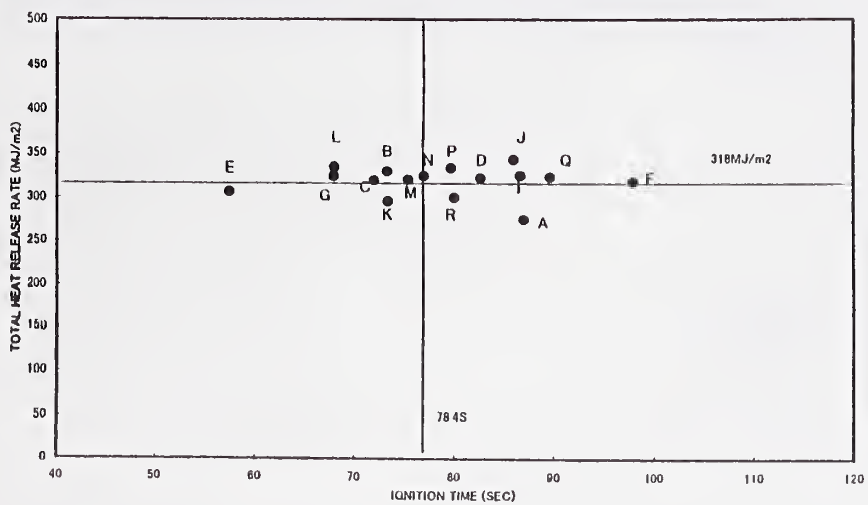


Figure 2(g) PMMA, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

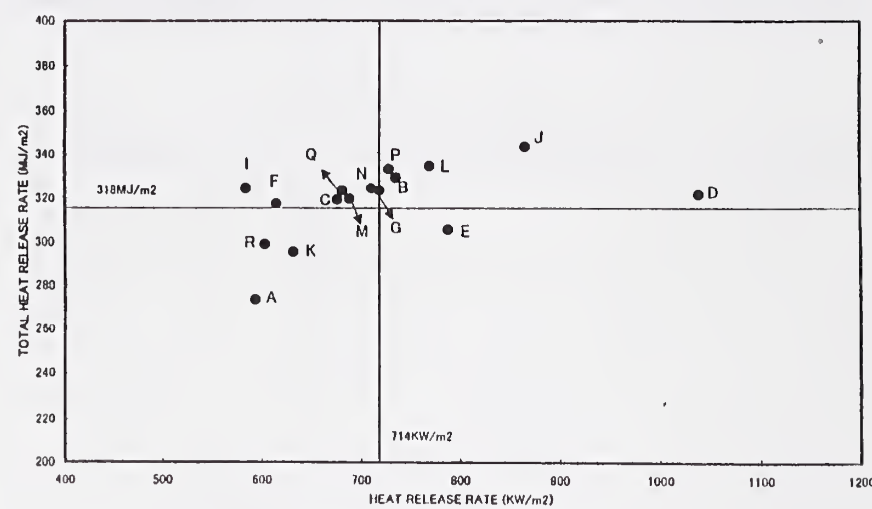


Figure 2(h) PMMA, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

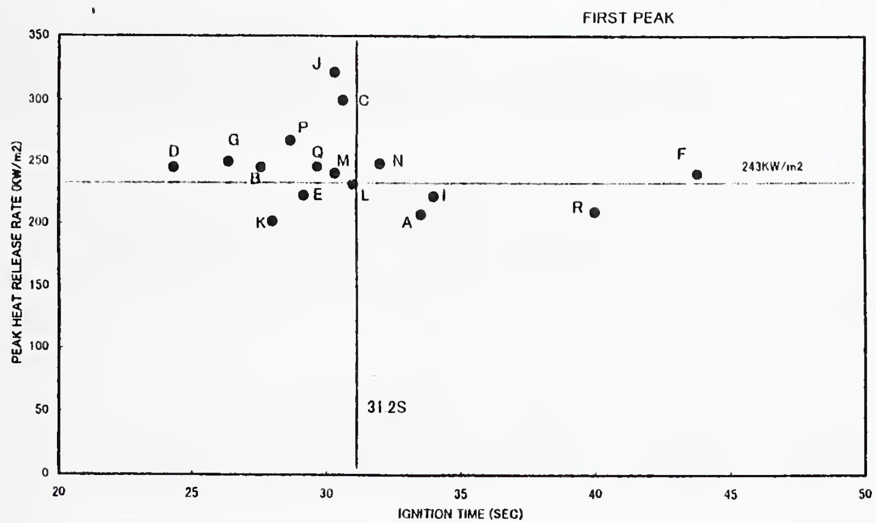


Figure 3(a) MDF, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 3(b) MDF, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

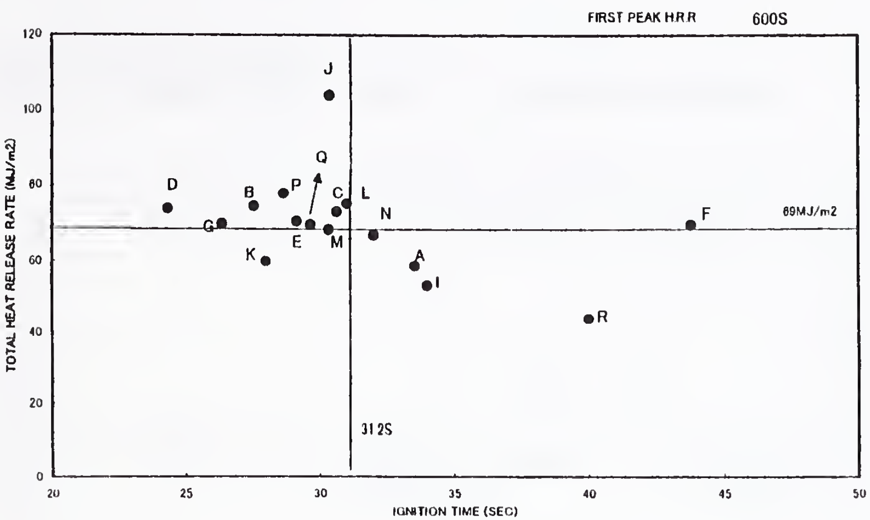


Figure 3(c) MDF, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

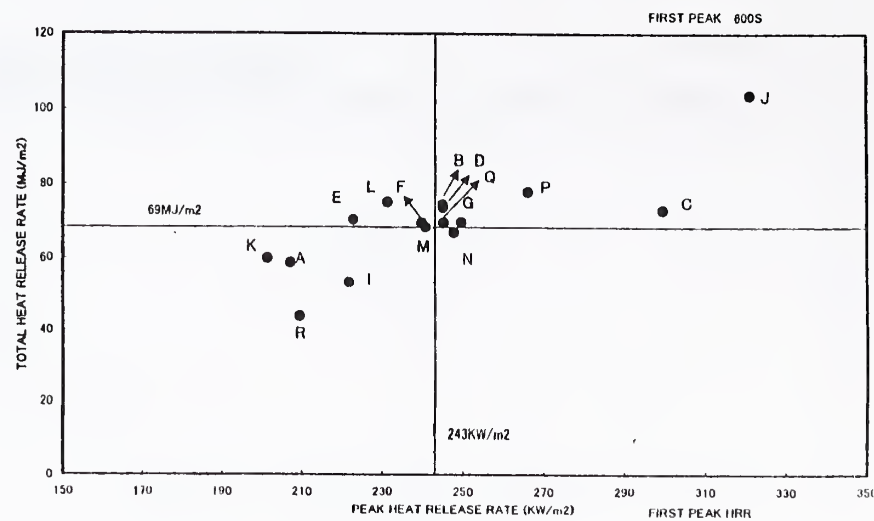


Figure 3(d) MDF, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

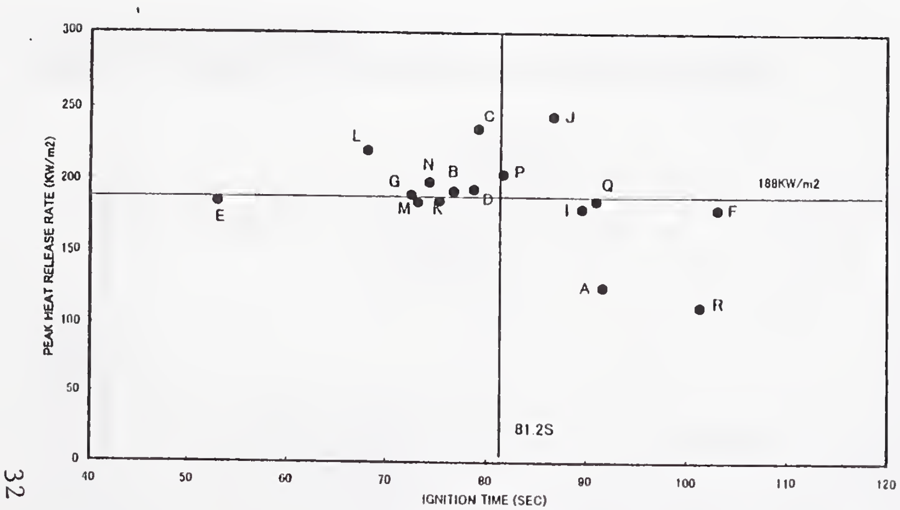


Figure 3(e) MDF, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 3(f) MDF, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

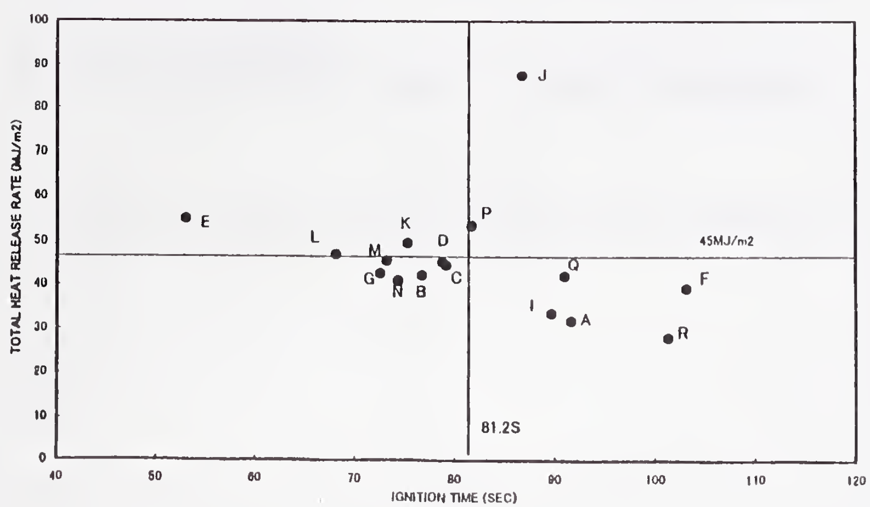


Figure 3(g) MDF, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

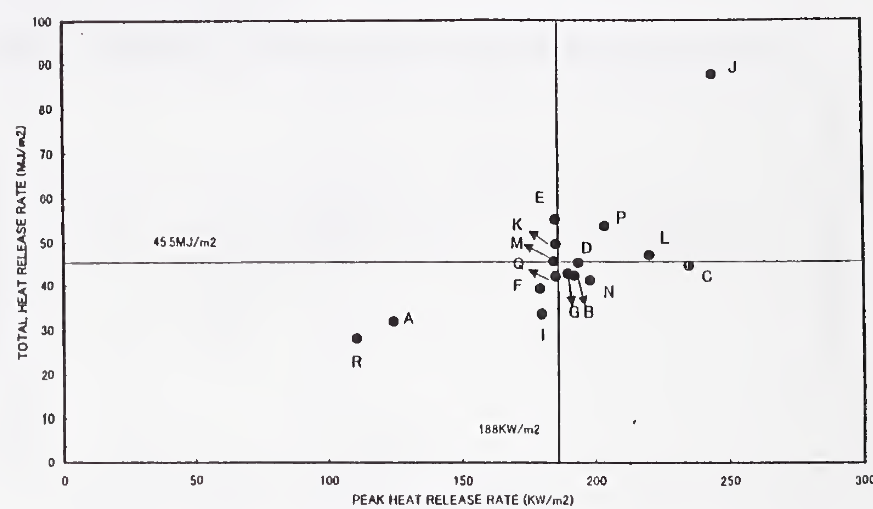


Figure 3(h) MDF, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

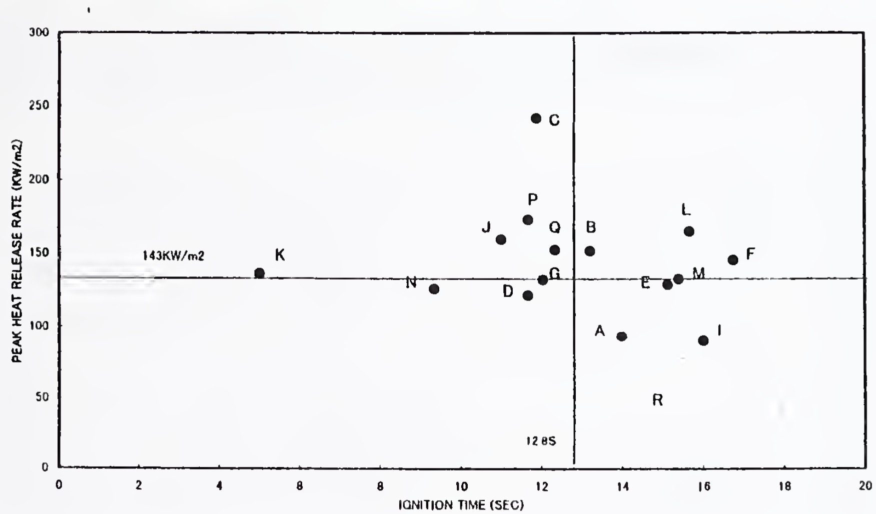


Figure 4(a) VCSP, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m^2

Figure 4(b) VCSP, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m^2

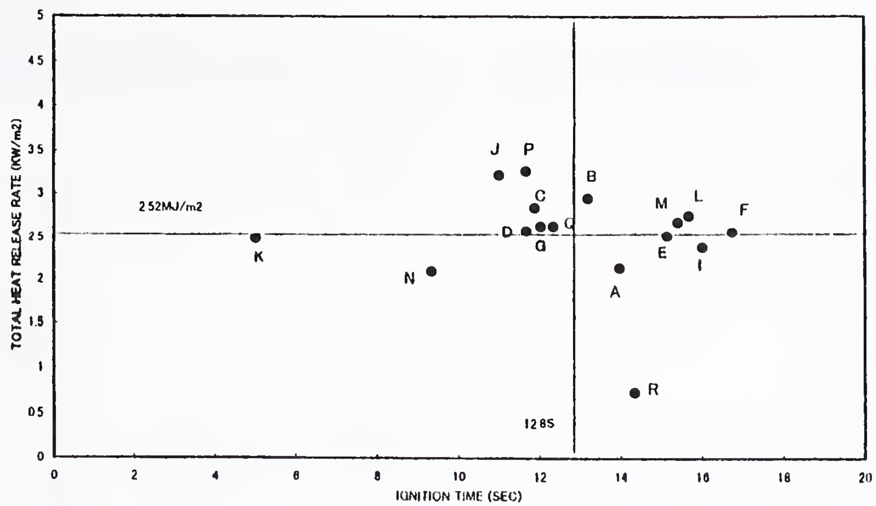


Figure 4(c) VCSP, Time to ignition vs. Total heat release
Heat flux level: 50kW/m^2

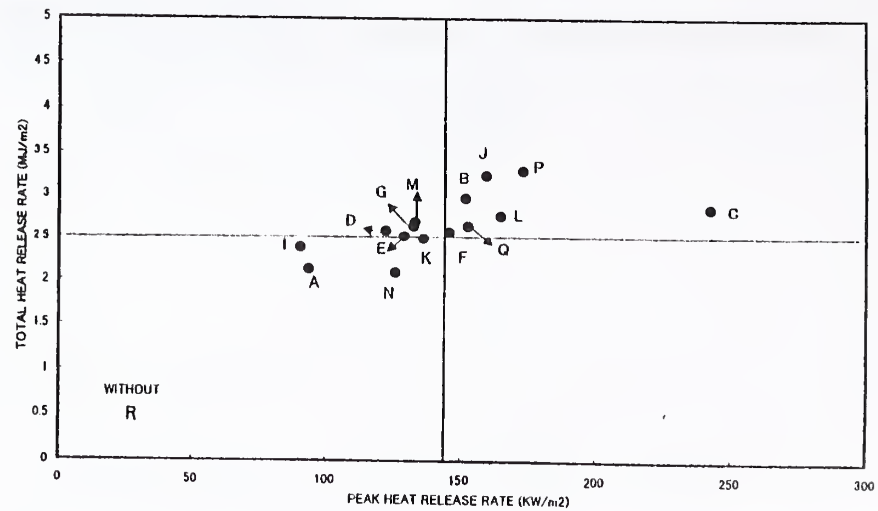


Figure 4(d) VCSP, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m^2

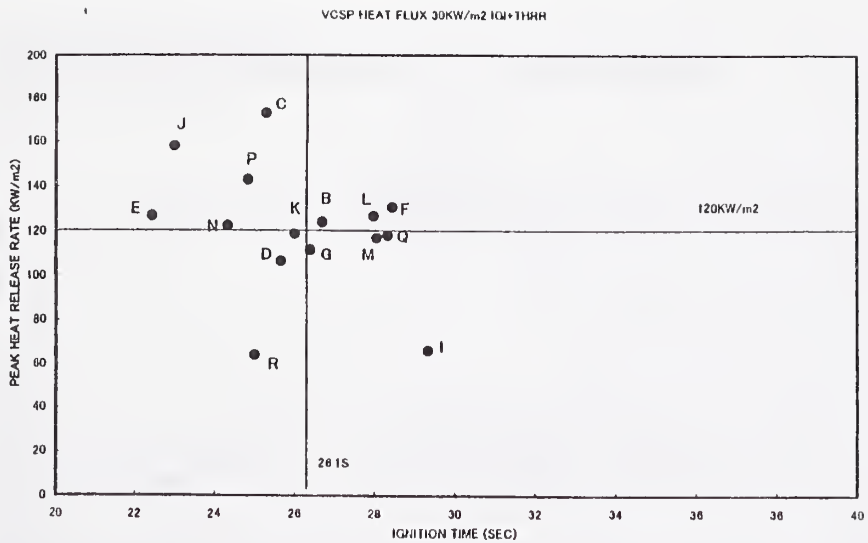


Figure 4(e) VCSP, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 4(f) VCSP, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

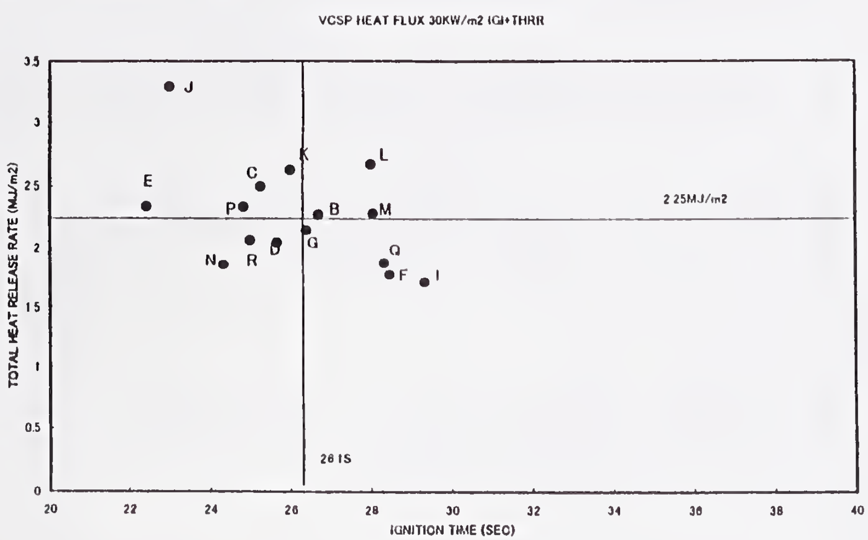


Figure 4(g) VCSP, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

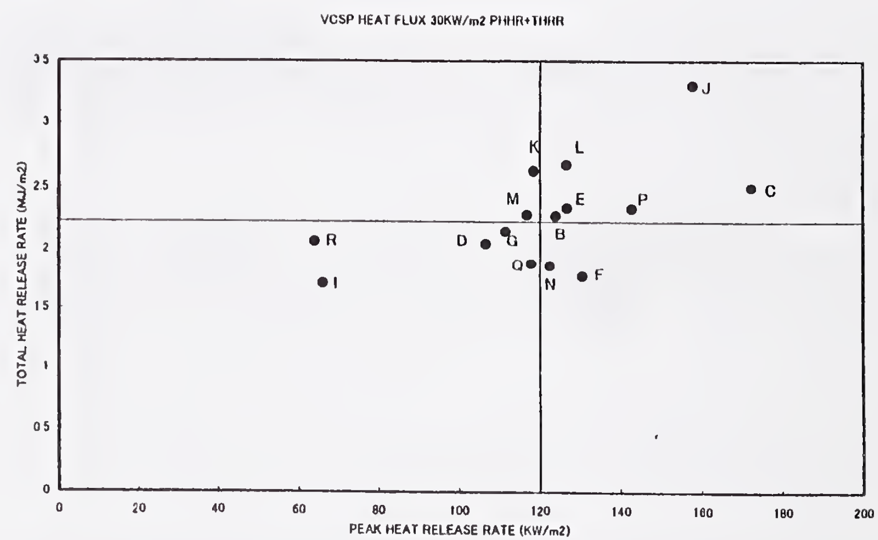


Figure 4(h) VCSP, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

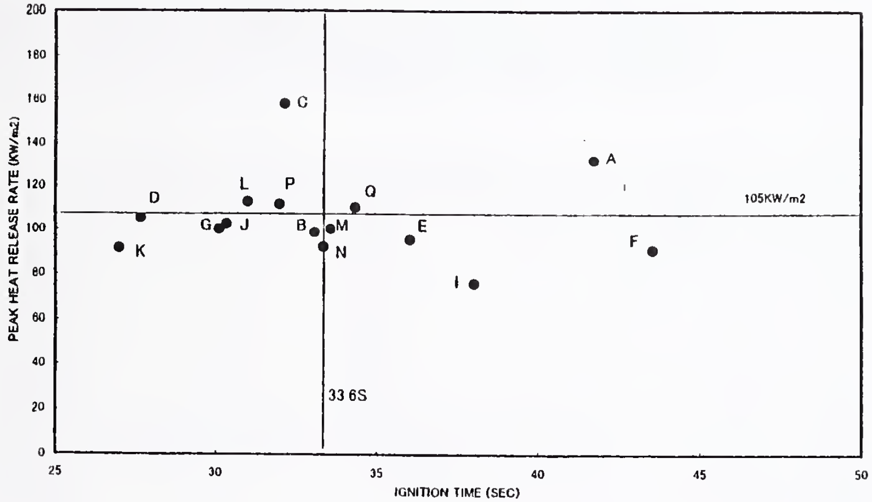


Figure 5(a) GB, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 5(b) GB, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

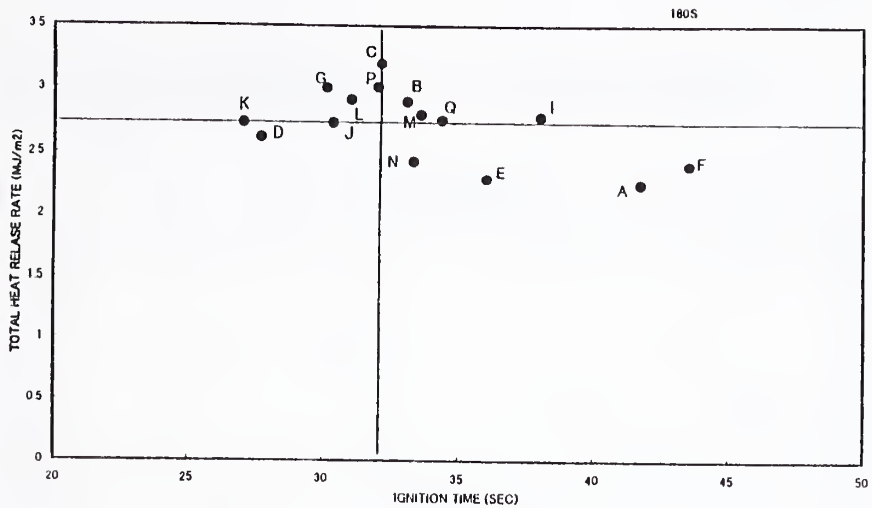


Figure 5(c) GB, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

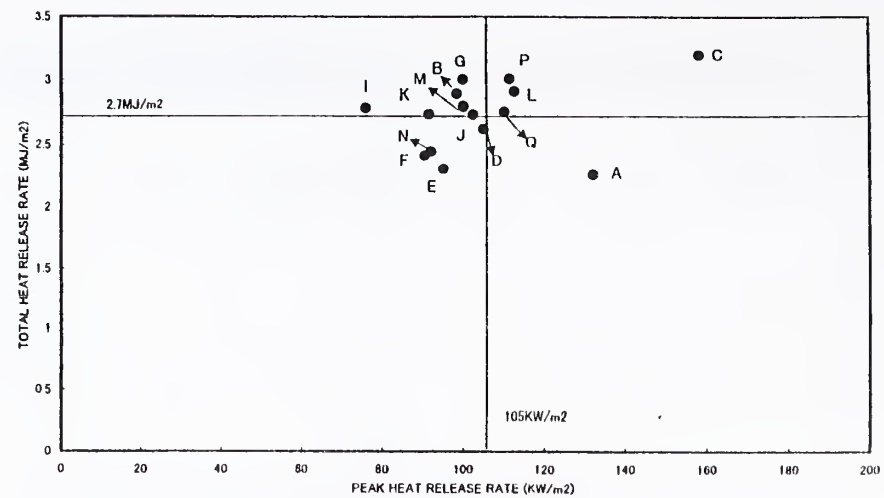


Figure 5(d) GB, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

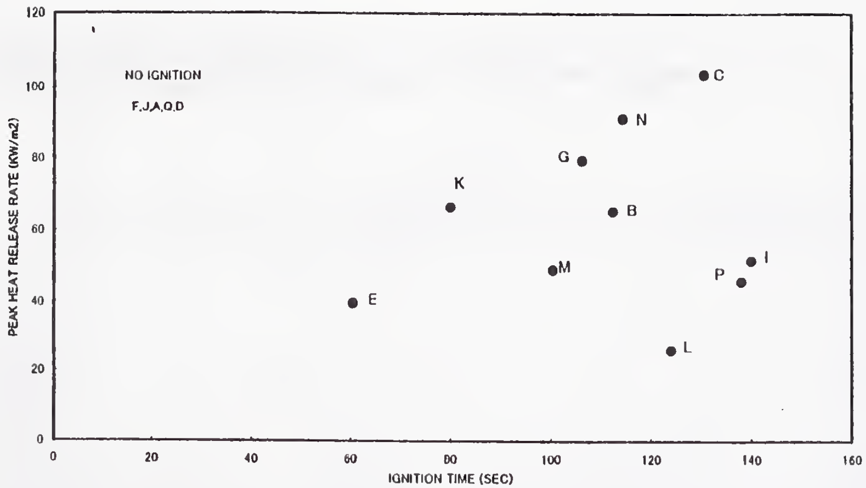


Figure 5(e) GB, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m^2

Figure 5(f) GB, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m^2

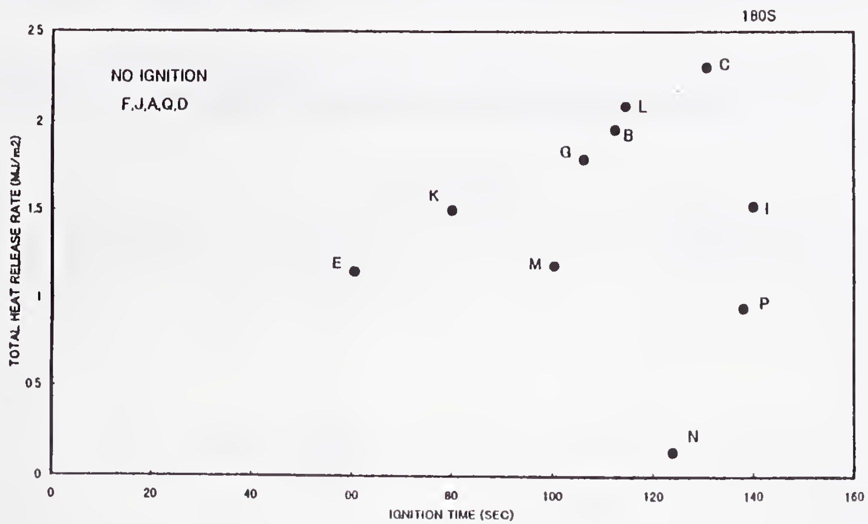


Figure 5(g) GB, Time to ignition vs. Total heat release
Heat flux level: 30kW/m^2

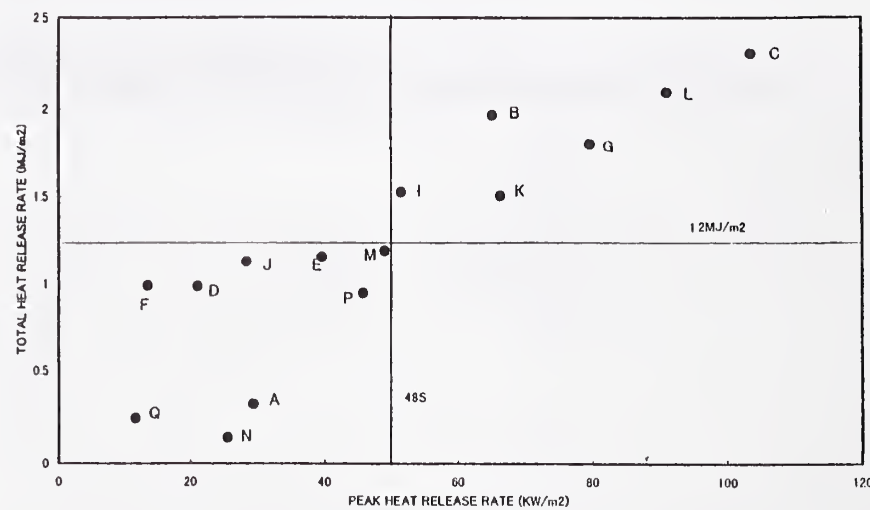


Figure 5(h) GB, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m^2

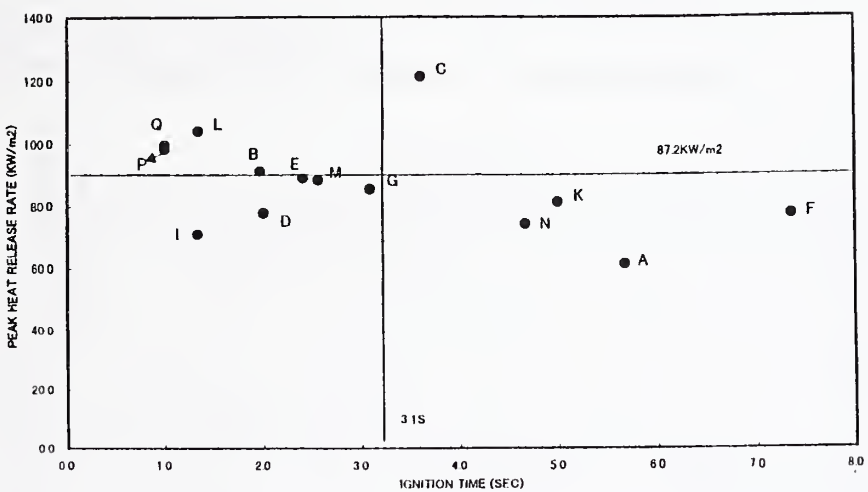


Figure 6(a) FGPC, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 6(b) FGPC, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

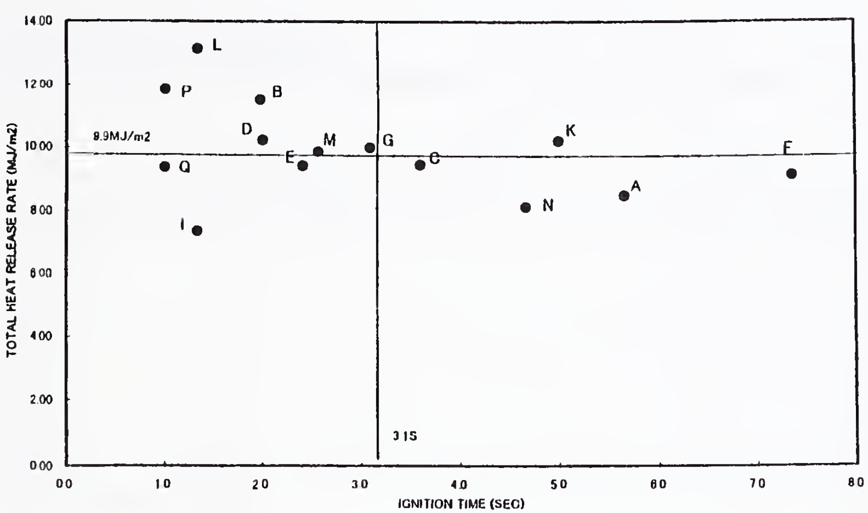


Figure 6(c) FGPC, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

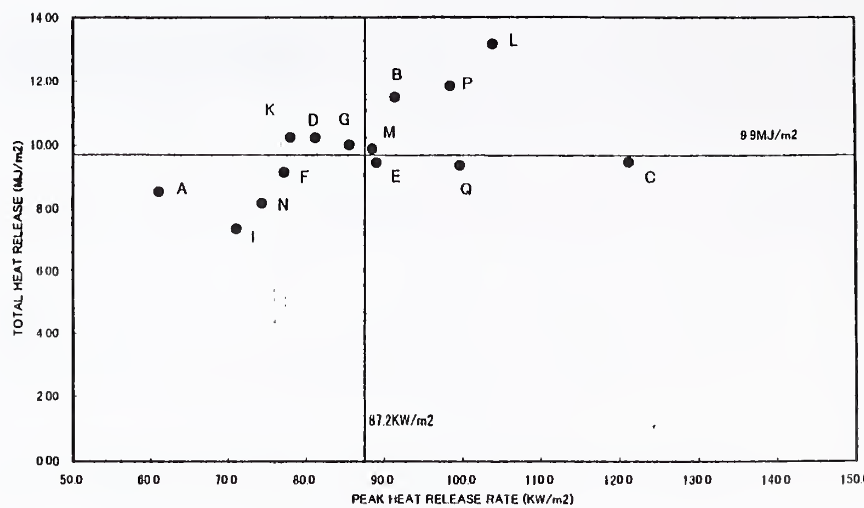


Figure 6(d) FGPC, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

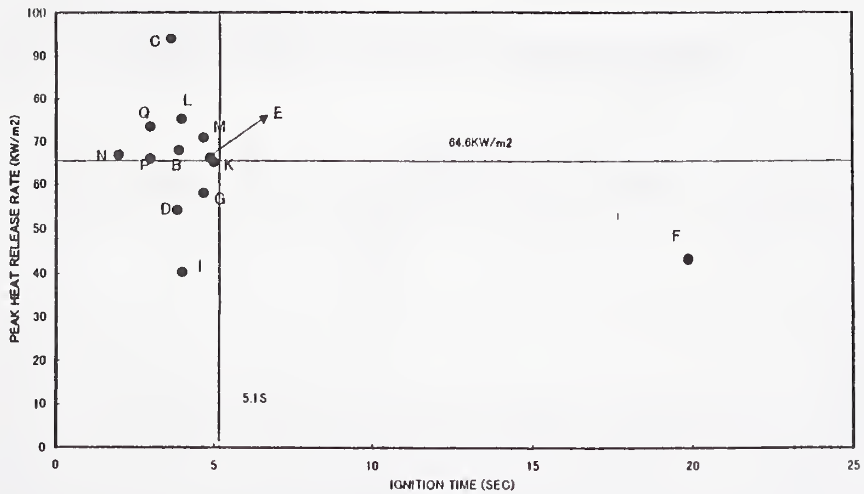


Figure 6(e) FGPC, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 6(f) FGPC, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

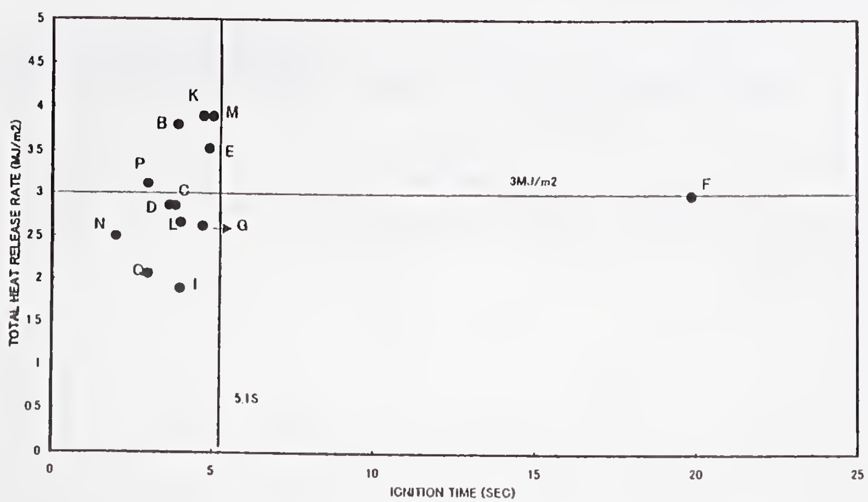


Figure 6(g) FGPC, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

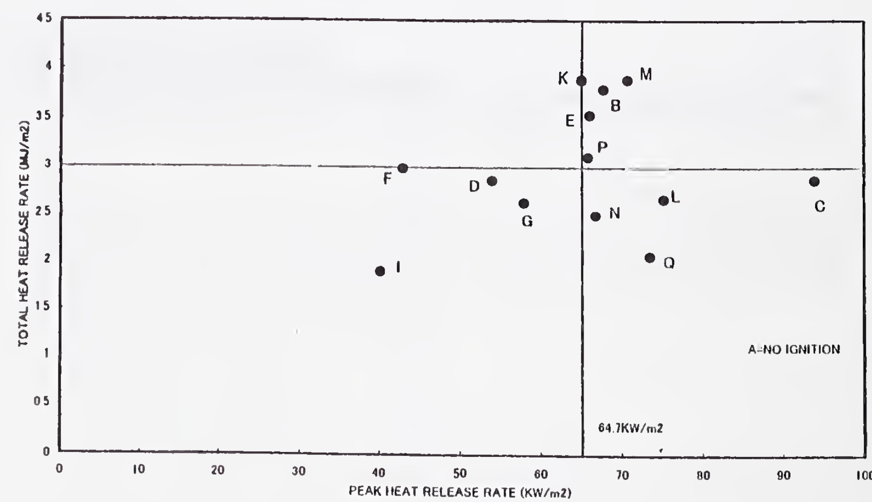


Figure 6(h) FGPC, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

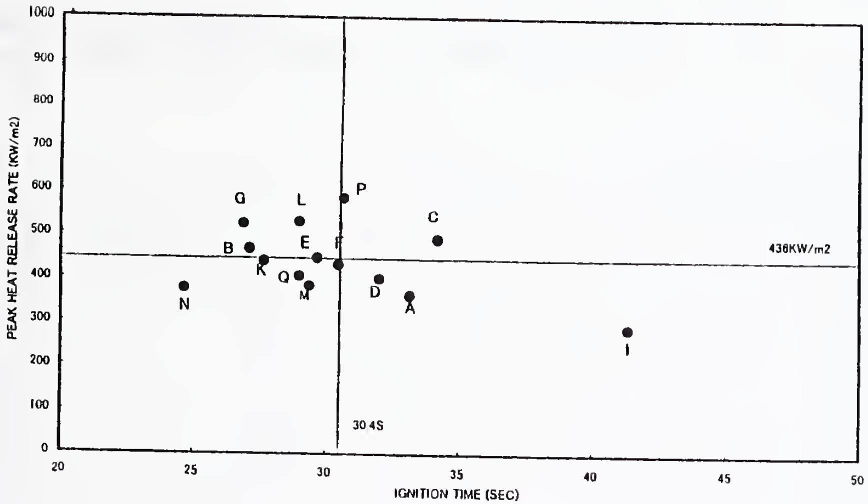


Figure 7(a) PS, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 7(b) PS, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

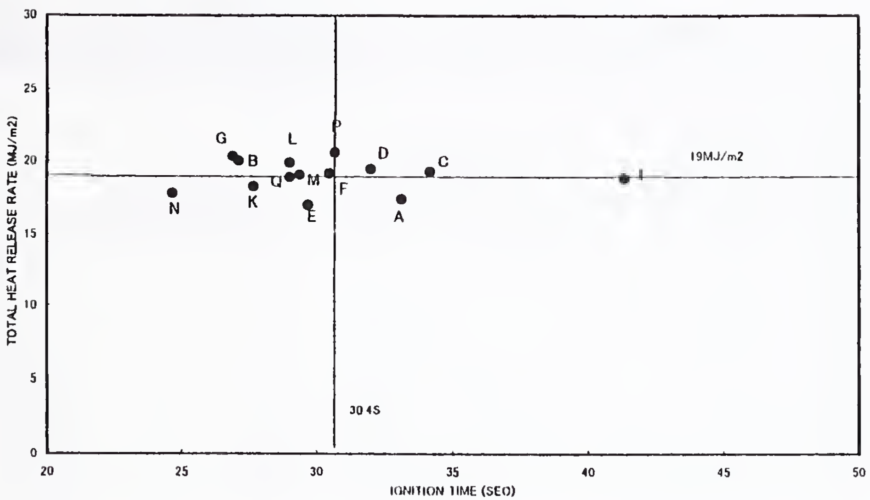


Figure 7(c) PS, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

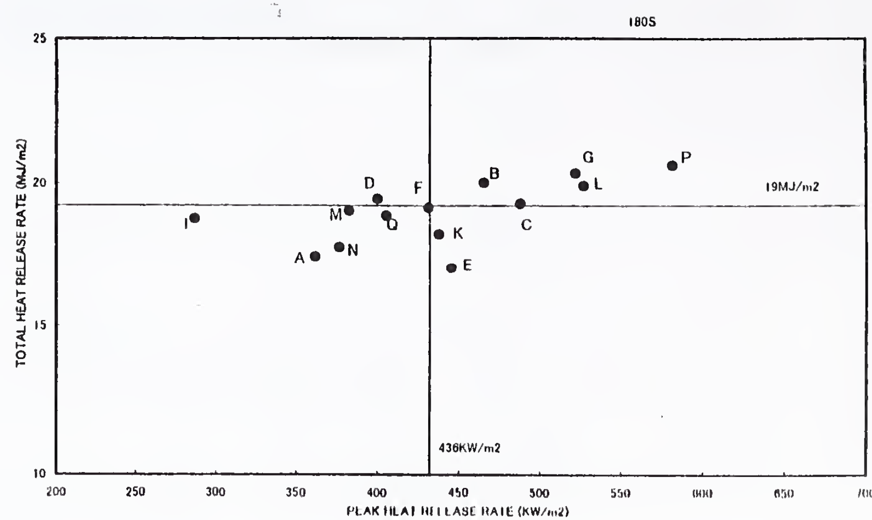


Figure 7(d) PS, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

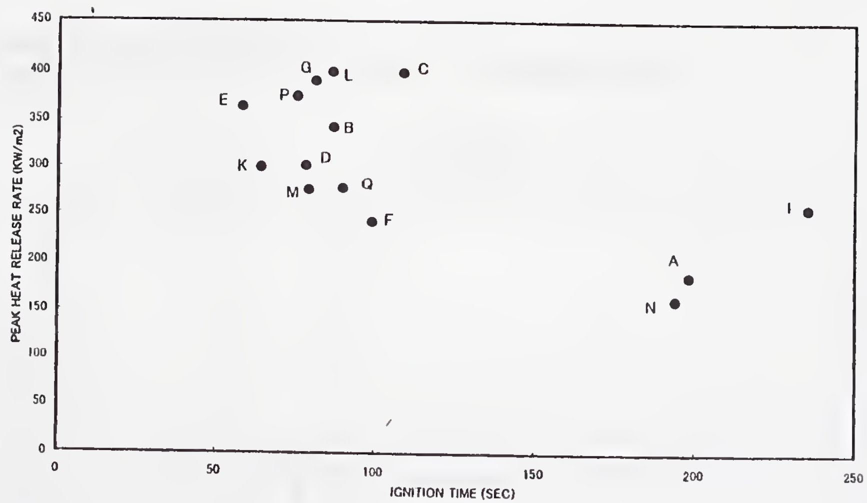


Figure 7(e) PS, Time to ignition vs. Peak heat release rate
Heat flux level: $30kW/m^2$

Figure 7(f) PS, Time to ignition vs. Plateau heat release rate
Heat flux level: $30kW/m^2$

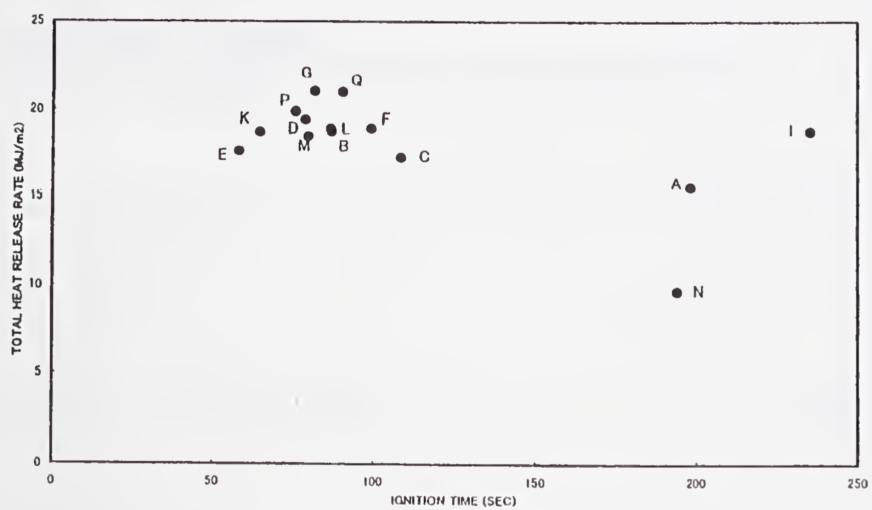


Figure 7(g) PS, Time to ignition vs. Total heat release
Heat flux level: $30kW/m^2$

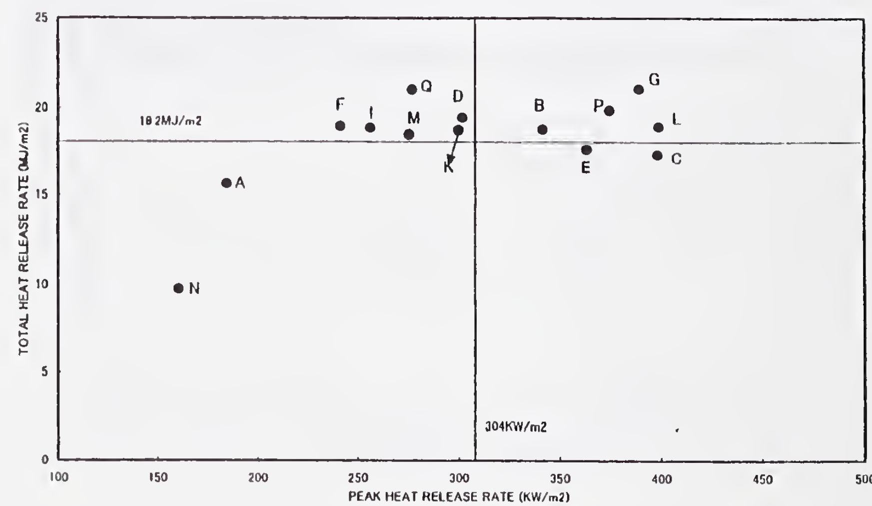


Figure 7(h) PS, Peak heat release rate vs. Total heat release
Heat flux level: $30kW/m^2$

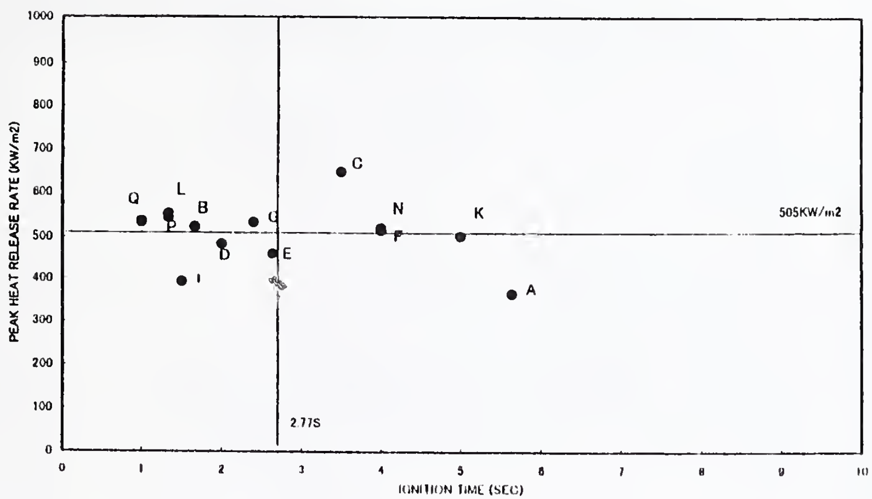


Figure 8(a) PU, Time to ignition vs. Peak heat release rate
Heat flux level: 50kW/m²

Figure 8(b) PU, Time to ignition vs. Plateau heat release rate
Heat flux level: 50kW/m²

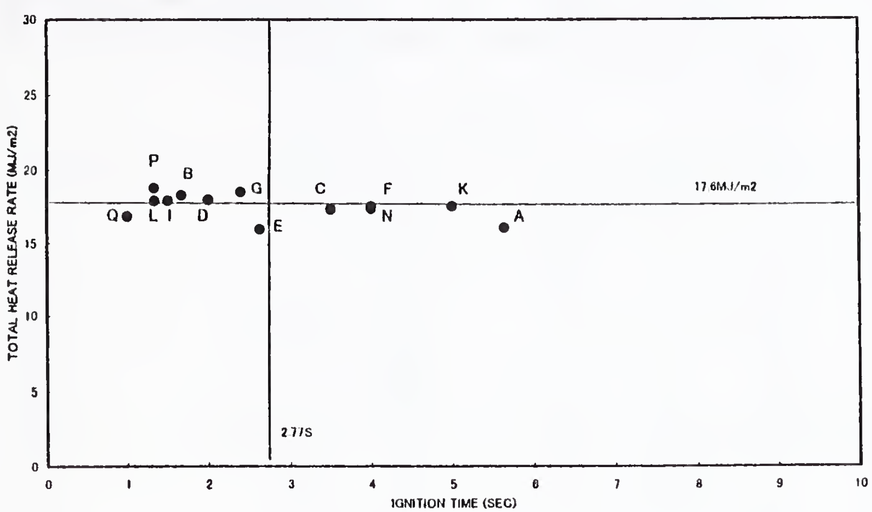


Figure 8(c) PU, Time to ignition vs. Total heat release
Heat flux level: 50kW/m²

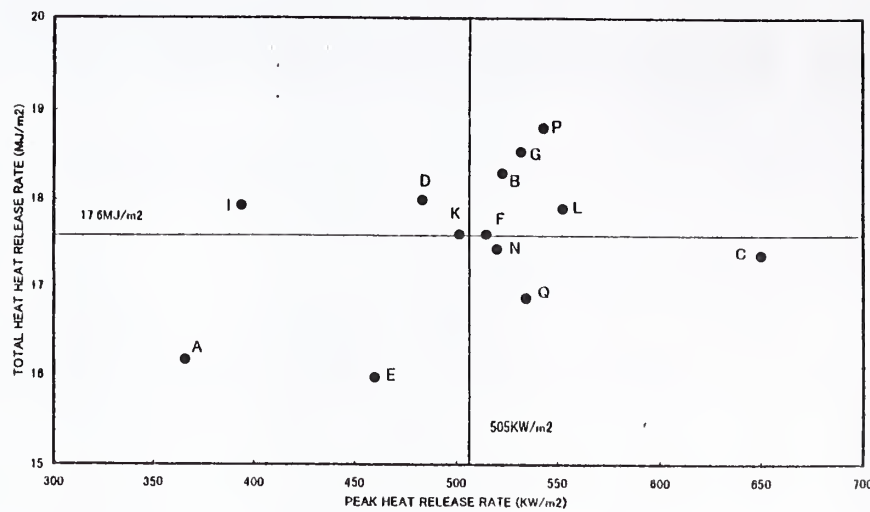


Figure 8(d) PU, Peak heat release rate vs. Total heat release
Heat flux level: 50kW/m²

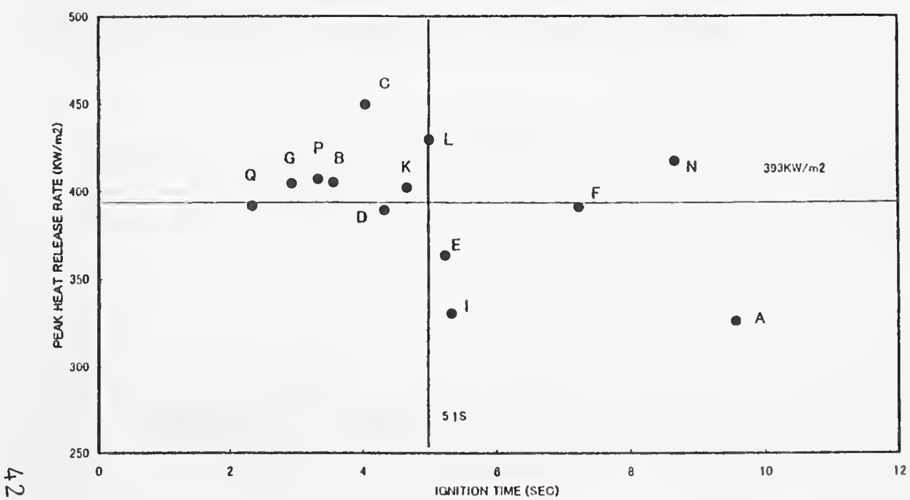


Figure 8(e) PU, Time to ignition vs. Peak heat release rate
Heat flux level: 30kW/m²

Figure 8(f) PU, Time to ignition vs. Plateau heat release rate
Heat flux level: 30kW/m²

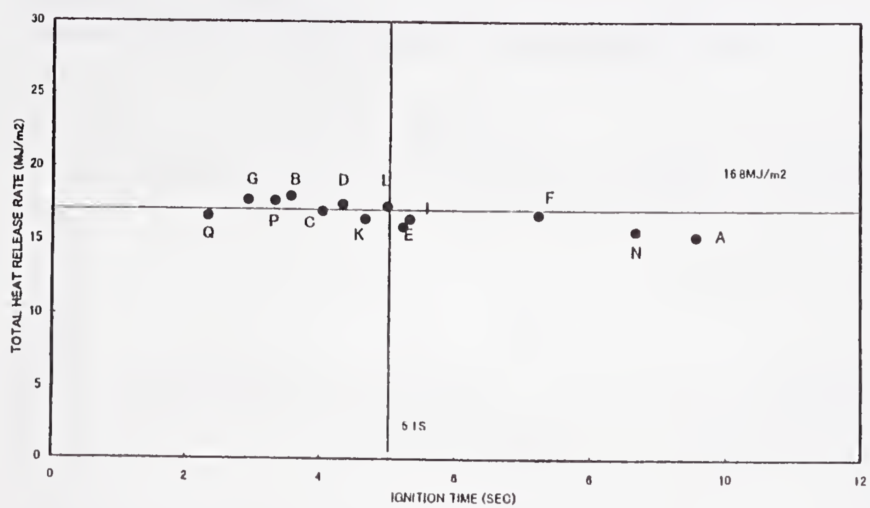


Figure 8(g) PU, Time to ignition vs. Total heat release
Heat flux level: 30kW/m²

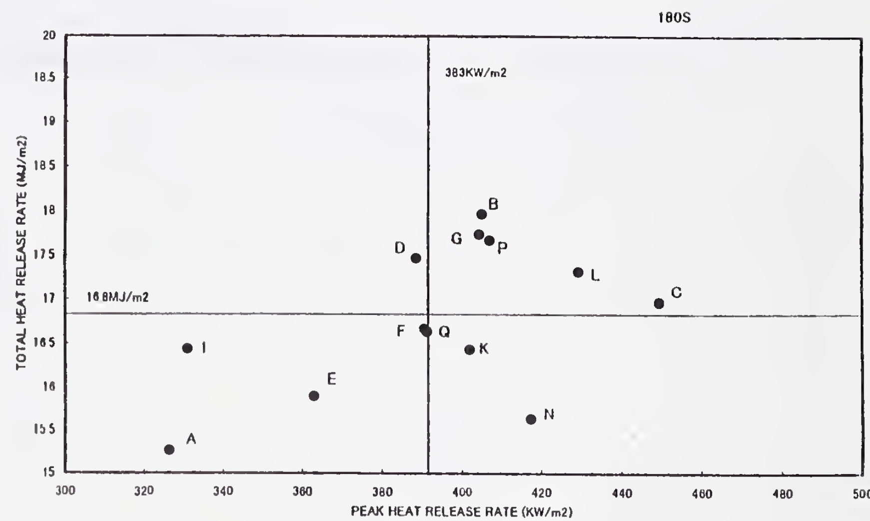


Figure 8(h) PU, Peak heat release rate vs. Total heat release
Heat flux level: 30kW/m²

BALANCED APPROACH TO THE FIRE PERFORMANCE EVALUATION OF INTERIOR FINISH MATERIALS

Marc L. Janssens and Scott E. Dillon
Southwest Research Institute
Department of Fire Technology
San Antonio, TX 78238

ABSTRACT

This paper describes a methodology for predicting the performance of interior finish materials in the ISO 9705 room corner test on the basis of material properties from small-scale tests (Cone Calorimeter and LIFT apparatus), and a relatively simple computer fire growth model (modified version of Quintiere's model). The heat release rate predictions are in good agreement with experimental room test data for a set of nine marine interior finish materials. The smoke predictions are in qualitative agreement with the measurements, but in some cases they err on the unconservative side. Therefore, additional work is needed to improve the smoke predictions.

INTRODUCTION

Room corner test procedures are now commonly used to evaluate the fire performance of interior finish materials. For example, U.S. model building codes specify acceptance criteria for textile wall coverings that are based on performance in the NFPA 265 or UBC 8-2 room test. The High Speed Craft Code (HSC Code) of the International Maritime Organization (IMO) allows for the use of combustible interior finish materials on small ferries, provided they meet stringent ISO 9705 room test criteria. Such materials are referred to as "fire restricting materials." For the recent development of new reaction-to-fire classification systems in Europe and Japan, the ISO 9705 room test was chosen as the reference scenario.

A research program was conducted at Southwest Research Institute (SwRI) between August, 1997 and July, 1998. The program was funded by the U.S. Coast Guard (USCG), who is the Authority Having Jurisdiction (AHJ) enforcing IMO regulations in the U.S. The primary objectives of the program were to establish acceptance criteria to qualify materials as fire restricting based on performance in the ISO 5660 Cone Calorimeter test, and to determine whether the general IMO surface flammability and smoke and toxicity requirements for finish materials are consistent with and perhaps redundant to the requirements for fire restricting materials. Eight glassfiber-reinforced plastic resin composite materials and one textile wall covering (see Table 1) were tested in full-scale in the ISO 9705 room. These tests were conducted with test specimens on the walls and ceiling of the 2.4 x 3.6 x 2.4 m room, using the standard propane gas burner source specified in ISO 9705 (100 kW exposure for 10 min, followed by 300 kW for 10 min) The same materials were also evaluated in small-scale according to the test procedures of the Cone Calorimeter (ISO 5660 and ASTM E 1354), the IMO surface flammability test [IMO Resolution A.653(16)], the Lateral Ignition and Flamespread Test or LIFT (ASTM E 1321), and the IMO smoke and toxicity test (IMO FTP Code, Part2).

Table 1. Materials Tested.

Material No.	Generic Name
1	FR Phenolic
2	Fire-Restricting Material
3	FR Polyester
4	FR Vinylester
5	FR Epoxy
6	Coated FR Epoxy
7	Wall Covering Material
8	Polyester
9	FR Modified Acrylic

A follow-up research program was conducted at SwRI in 1999 for Hughes Associates Inc. in Baltimore, MD, as part of a larger program performed by Hughes for the USCG. The objective of this program was to evaluate different models of the ISO 9705 room corner test on the basis of the experimental data obtained during the previous program at SwRI, and possibly modify the models to improve agreement between predictions and experimental results. As a starting point we used the model developed by Quintiere in its original form, in conjunction with material properties obtained according to the procedures proposed in Quintiere's seminal paper [1]. Unfortunately, the resulting calculations were in poor agreement with the experimental room test data. Therefore, the procedures for obtaining material properties, as well as the model itself were modified to improve agreement with the experimental data. These changes are discussed in some detail below.

IGNITION PROPERTIES

Procedures to obtain material properties from piloted ignition data at different heat flux levels commonly assume that the surface heat losses partly involve Newtonian cooling which is characterized by a constant convection coefficient. Recent measurements at SwRI show that the convection coefficient in the Cone Calorimeter, for specimens in the horizontal orientation tested with the retainer frame, can be expressed as a linear function of the external heat flux from the Cone heater:

$$h_c \equiv h_0 + h_1 \dot{q}''_e \qquad (1)$$

where h_0 = 11.8 W/m²·K and h_1 = 0.00034 1/K at heat flux levels below 50 kW/m², and h_0 = 25.5 W/m²·K and h_1 = 0.000065 1/K at heat flux levels equal to or greater than 50 kW/m².
Consider a semi-infinite solid with constant properties k, ρ, and c exposed to a constant radiant heat flux, $\dot{q}''_e$, with radiative and convective heat losses from the surface:

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \qquad (2.a)$$

with

$$T = T_\infty \qquad t = 0, \text{ and } x \geq 0 \qquad (2.b)$$

and

$$\varepsilon \dot{q}''_e = h_c (T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_\infty^4) \qquad (2.c)$$

where T_s is the temperature at the surface ($x = 0$), and T_∞ is the initial and ambient temperature. The solution of Equations (2.a)-(2.c) can be expressed by the following relationship between the time, t_{ig}, to reach surface temperature $T_s = T_{ig}$, and the incident heat flux $\dot{q}''_e$ [2]:

$$\dot{q}''_e = \sigma(T_{ig}^4 - T_\infty^4) + \frac{h_c}{\varepsilon}(T_{ig} - T_\infty) + \frac{0.71(T_{ig} - T_\infty)}{\varepsilon}\left(\frac{k\rho c}{t_{ig}}\right)^{0.5} \qquad (3)$$

Substitution of Equation (1) into Equation (3), after rearranging, leads to

$$\left(\frac{k\rho c}{t_{ig}}\right)^{0.5} = C_1 \dot{q}''_e - C_0 \qquad (4.a)$$

where

$$C_1 = \frac{\varepsilon}{0.71(T_{ig} - T_\infty)} - \frac{h_1}{0.71} \qquad (4.b)$$

and

$$C_0 = \frac{\varepsilon\sigma(T_{ig}^4 - T_\infty^4)}{0.71(T_{ig} - T_\infty)} - \frac{h_0}{0.71} \qquad (4.c)$$

Equation (4.a) suggests that $(1/t_{ig})^{0.5}$ be plotted as a function of $\dot{q}''_e$. The intercept of a straight line fitted through the data points is equal to C_0/C_1, which can be used to determine T_{ig}. Once the surface temperature at ignition is known, $k\rho c$ can be calculated from the slope of the linear fit. Because h_0 and h_1 have different values for heat fluxes below and above 50 kW/m², the slope of the linear fit is slightly smaller at heat fluxes below 50 kW/m². This procedure was used to recalculate the ignition properties for the nine materials.

FLAME SPREAD PROPERTIES

The ASTM E 1321 LIFT data analysis procedure specifies that $1/\sqrt{V(x)}$ be plotted as a function of $\dot{q}_e''(x)$, and a straight line be fitted through the data points. The flame heating parameter ϕ is calculated from the slope C as follows:

$$\phi = \frac{k\rho c}{C^2 h_{ig}^2} \tag{5}$$

Since the ignition properties have changed, the flame heating parameter was recalculated.

HEAT RELEASE RATE PROPERTIES

The simulations with the original version of Quintiere's model generally underestimates fire growth. This is attributed, at least in part, to high heat of gasification values. To eliminate this problem, it was decided to use actual Cone Calorimeter heat release rate curves, instead of heat release properties derived from Cone data. The Cone Calorimeter data show that heat flux effects are not significant for most materials, and the experimental data at 50 kW/m² were selected for (an initial) analysis. Quintiere [1] uses an incident heat flux of 60 kW/m² for the ISO 9705 ignition burner flames and 30 kW/m² for a vertical wall flame. However, experiments by Dillon [3] and calculations by Janssens [4] indicate that a heat flux of 45 to 50 kW/m² may be more appropriate for the ISO 9705 burner with an output of 100 kW. Therefore, the selection of Cone Calorimeter data at 50 kW/m² is reasonable for this analysis. For materials that did not ignite at 50 kW/m², the Cone Calorimeter results at 75 kW/m² were used instead. The average heat release curve for all runs conducted at 50 (or 75 kW/m²) was approximated by an exponentially decaying function, as shown below:

$$\begin{array}{lll} 0 \le t - t_{ig} \le 30 & : & \dot{Q}'' = HRR_{30,max} \\ 30 \le t - t_{ig} \le t_b & : & \dot{Q}'' = HHR_{30,max} e^{-\lambda(t - t_{ig} - 30)} \\ t - t_{ig} > t_b & : & \dot{Q}'' = 0 \end{array} \tag{6}$$

The decay parameter λ is determined such that the area under the curve is equal to the average total heat release rate measured in the Cone Calorimeter experiments. The idea to use an exponentially decaying function was based on earlier work by Magnusson and Sundström [5]. The maximum 30-sec sliding average heat release rate was used instead of the peak, because the former has been proposed as one of the criteria to qualify fire-restricting materials on the basis of Cone Calorimeter data [6].

SMOKE RELEASE RATE PROPERTIES

A method was developed to obtain a rough estimate of the smoke production rate in the ISO 9705 room-corner test. The heat release rate of the wall material is divided by the heat of

combustion (based on Cone Calorimeter data obtained at 50 or 75 kW/m^2). The resulting mass loss rate is multiplied with the specific extinction area, σ, measured in the Cone calorimeter to determine the smoke production rate.

MODIFICATIONS TO THE MODEL

The geometry of the burning area was simplified based on equations previously used by Janssens [2] in his QBasic version of the Quintiere model. The pyrolysis and burned out areas are represented by rectangular areas as opposed to complex trapezoids. Algorithms were also included that better describe the geometry and thermal environment created by the ignition source. The heat flux to the material in contact with the burner flame is determined based on the heat output of the burner and the temperature of the material, as opposed to simply using a constant flux.

Equations to estimate heat release rate on the basis of the heat of combustion, heat of gasification, and net heat flux were replaced with calculations on the basis of the exponentially decaying curve. The total heat release rate from the wall material at time t is given by

$$HRR(t) = \sum_{i=1}^{t} (A_i - A_{i-1})\dot{Q}''(t-i) \tag{7}$$

where A_i and A_{i-1},are the burning areas at time i and i-1 seconds, respectively. As the flame front progresses, the pyrolysis area increases. At every incremental time step, a new area may ignite and start burning. The modified model tracks and sums the heat release rate from each incremental area based on the exponentially decaying heat release rate curve to determine the total heat release rate from the material. This method automatically accounts for burnout, i.e., an incremental area burns out when its heat release rate reaches the end of the exponential curve.

Routines were also added to estimate the smoke production rate, SPR, and the corresponding emissivity of the hot gas layer, ε_g. The smoke production rate is calculated as the heat release rate divided by the heat of combustion and multiplied by the specific extinction area measured in the Cone Calorimeter.

The emissivity of the upper gas layer is also calculated as a function of the specific extinction area. Quintiere's original model assumes $\varepsilon_g = 1$, which appears to be overly conservative for low smoke producing materials. The emissivity of a hot and smoky gas layer can be estimated from [7]

$$\varepsilon_g = 1 - \exp\left(-(0.33 + 0.47C_s)(H - Z_i)\right) \tag{8}$$

where C_s is the concentration of soot particles (g/m^3), H is the room height (m), and Z_i is the layer interface height (m). The soot concentration can be estimated from

$$C_s = \frac{SPR}{k_m \dot{V}_o} = \frac{\sigma HRR(t)}{k_m \dot{V}_o \Delta H_c} \tag{9}$$

where $k_m = 7.6\ m^2/g$ based on data by Seader and Einhorn for flaming wood and plastics fires [8]. The layer depth was set equal to 1 m, based on observations in the ISO 9705 tests. To obtain a conservative (high) estimate of ε_g, a volumetric vent flow of 0.5 m^3/s was chosen. The resulting ε_g estimates vary between 0.4 and 1.0.

MODIFIED MODEL SIMULATIONS

The heat release rate predictions are in good agreement with the measurements. Typical examples are shown in Figures 1 and 2. Table 2 compares measured and predicted flashover times, with flashover defined as the moment when the total heat release rate in the room reaches 1000 kW (except for material No. 5, for which 750 kW was used, based on visual observations during testing). For the materials with a flashover time less than 600 s (Nos. 3, 4, 8), the model predictions are very close to the measured heat release rate. For materials with flashover times between 600 and 1200 s (Nos. 5 and 9), the predicted flashover times fall within the same 300-kW exposure period. For the remaining materials, the model correctly predicted that flashover does not occur, and that the heat release criteria for fire restricting materials are not exceeded. However, two of the four materials (No. 1 and No. 6) marginally failed the smoke requirements for fire restricting materials, while the model predicted that all four materials would meet the smoke requirements.

Table A2. Comparison of Measured and Predicted Flashover Times.

Material No.	Experimental (s)	Model (s)
1	No flashover	No flashover
2	No flashover	No flashover
3	342	345
4	306	305
5	***978***	***666***
6	No flashover	No flashover
7	No flashover	No flashover
8	102	56
9	672	611

Bold Italic: Time to 750 kW

CONCLUSIONS

A modified version of Quintiere's fire growth model was developed to predict performance of wall and ceiling linings in the ISO 9705 room-corner test. Good quantitative agreement was found between the predicted and measured heat release rates for a set of eight marine composite materials and one textile wall covering.

Although the flame spread data were developed, it was found that lateral flame spread had an insignificant effect on material performance in the ISO 9705 test. Therefore, it is suggested that LIFT and IMO surface flammability test data are unnecessary for performing predictions by the method presented in this report. This can be advantageous due to the high cost of lateral flame spread tests in comparison with Cone Calorimeter tests.

A first attempt was made at estimating the smoke production rate on the basis of the specific extinction area measured in the Cone Calorimeter. The smoke predictions are in qualitative agreement with the measurements, but in some cases they err on the unconservative side. Therefore, additional work is needed to improve the smoke predictions.

A major benefit of the proposed procedure is that a minimal amount of small-scale data is needed to predict ISO 9705 room test performance. It is sufficient to test a material in the Cone Calorimeter at an heat flux level of 50 kW/m^2, provided the sample is instrumented with a thermocouple on the exposed surface to measure the surface temperature at ignition.

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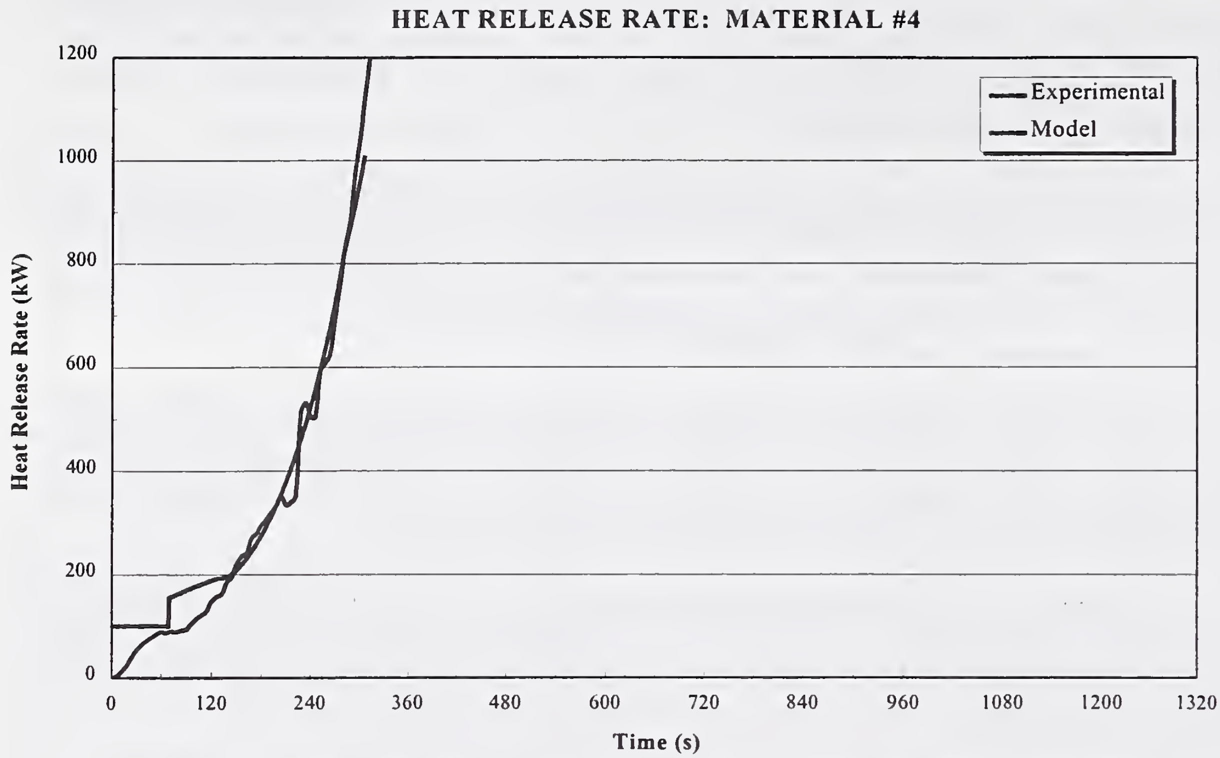

Figure 1. Best agreement between predicted and measured heat release rates

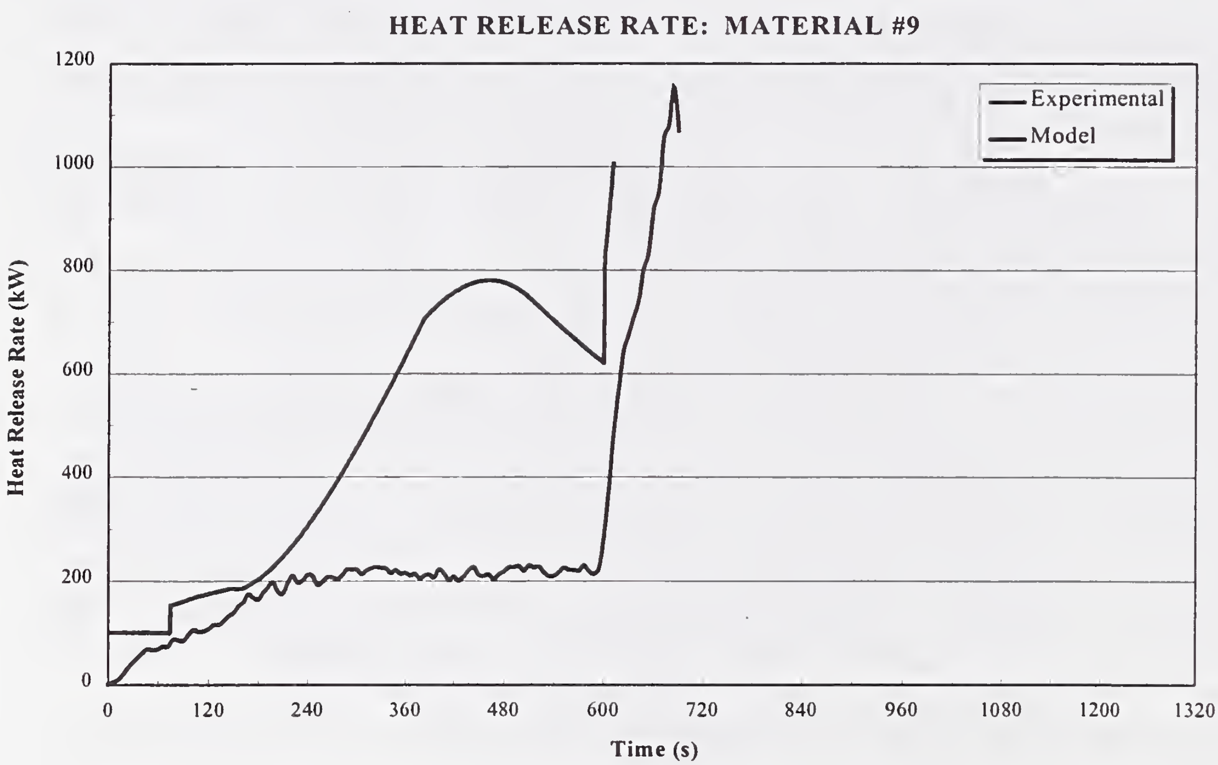

Figure 2. Poorest agreement between predicted and measured heat release rates

CORRELATIONS BETWEEN BENCH-SCALE TEST AND ROOM CORNER TEST BASED ON A FLAME SPREAD MODELING

INTERPRETATION OF SMALL AND INTERMEDIATE SCALE FIRE TESTING

Yuji Hasemi
School of Science and Engineering, Waseda University

Masashi Yoshida and Yoshihiko Hayashi
Building Research Institute, Ministry of Construction

and

Takatoshi Yabuta
formerly Science University of Tokyo

ABSTRACT

A framework and indices to classify fire hazard of lining materials directly using row data from bench scale test are developed by the analysis of the qualitative and asymptotic behavior of concurrent flame spread models. The proposed index uses total heat release rate, time to ignition and time to burnout. Through comparative studies, this method has been found to lead to a reasonable correlation between the results of the Cone Calorimeter and the ISO9705 Room Corner Test.

Keywords: *Cone Calorimeter, ISO 9705 Room Corner Test, flame spread, heat release rate, flashover.*

INTRODUCTION

Upward flame spread along a wall lining and horizontal flame development beneath a combustible ceiling is very often a direct trigger for the occurrence of flashover. Although the fear of concurrent flame spread should have been recognized from the dawn of the civilization, development and application to practice of Fire Safety Engineering(FSE) concepts and tools for lining materials is still far behind that in the smoke control and the structural fire safety. This is probably because of the complexity of the phenomena relevant to the fire safety of interior linings. Because of such difficulty in the engineering approach, most of the conventional regulations and tests on lining materials do not seem to have clear relevance with real fires. Moreover, comparative studies on standard reaction-to-fire tests in European countries during the 1960's revealed notable inconsistency in the then effective regulatory test methods[1]. Such inconsistency raised a doubt if the conventional classification properly represents the hazard of lining materials in real fires.

On the other hand, modeling of concurrent flame spread is probably one of the research topics in fire safety on which the progress of scientific understanding have been the most pronounced during the last two decades. Concurrent flame spread attracted combustion scientists relatively early, and the theoretical paradigm for its mathematical formulation was established before the 1980s[e.g.2, 3, 4, 5]. Most of the early works on flame spread, conducted within the combustion science rather than fire research, dealt with simple materials, laminar flow conditions and idealized configurations with few exceptions[6]. Modeling of flame spread in the fire safety engineering since around the 1980s has focused the treatment of turbulence, development of simulation method, reformulation using material properties measurable with practical testing apparatus as input, and the derivation of evaluation concepts for fire safety. These efforts have enabled prediction of concurrent flame

spread for limited types of lining materials and the evaluation of the asymptotic behavior of fire development. These research efforts have been reflected in the development of performance-oriented reaction-to-fire tests by the ISO/TC92/SC1(reaction-to-fire). However, the complexity of the lining fires still seems to prevent practitioners such as building regulators, architects and material producers to introduce these research results into practice.

Most of the flame spread models in fire are based on a concept of ignition and flame spread as a result of inert heating of the solid to an ignition temperature(Figure 1). These models could be divided into two types; analytical and numerical models. Analytical models[e.g.7, 8, 9,10] generally introduce simplifications and assumptions whereas numerical ones[e.g.11,12] generally try to divide the combustible surface into finite difference grids and calculate the surface temperature of each grid. Numerical approach can deal with the precise distribution of the flame heat transfer and do not necessarily introduce any simplification. The benefit of the analytical approach is the ease to predict asymptotic and global behavior of the flame spread, e.g. autonomous flame extinction and the divergence of the solution. Another profit of analytical approach compared with numerical one in the light of practice, is probably that numerical models generally need such elementary properties of materials as thermal conductivity, density, specific heat and heat of combustion, which need to be measured individually and can be difficult for practical building materials.

NEEDS OF MODELING BASIS FOR MATERIAL CLASSIFICATION

Large scale and intermediate scale experiments on wall fires were conducted for the fire safety design of the wooden lining of the main theater of Japan's recently completed New National Theater. Since the design chosen by an international competition in 1986 proposed wooden lining and was against the Building Standard Law, Japan's Ministry of Construction(MoC) organized a project for its fire safety design[13]. Thickness, surface finish and other design features of the wooden wall lining was finally determined to localize the wall burning to less than three times the height of the pilot flame above the first ignited package. Although this project was useful to promote research on the combustible lining and flame spread in Japan, it is obvious that such investigations were possible only because it was a very large construction project.

In the application of engineering fire prediction to the practical fire safety design of interior linings, there are however at least two types of difficulties. First difficulty relates to the considerable sensitivity of the growth of a compartment fire to the fire source and other initial and boundary conditions. In spite of the importance of such conditions for fire growth, it is generally difficult to predict these conditions since they may change almost everyday or according to occupants. Such difficulty should be more pronounced as the room becomes smaller, because the smoke layer temperature and the interactions of radiation heat transfer tend to be augmented in small enclosures although these conditions are the dominating elements for the growth of a room fire. The another difficulty relates to the limitation in the man power and funds available for the design of interior linings in "common buildings". Despite such complexity in the prediction of lining fires, time, man power and funding allowance for the interior design of a common building is generally not enough to run mathematical models on different fire scenarios.

For the fire safety design of "common buildings", classification is believed to be still a most functional way for lining materials; the central problem for establishing a classification of materials within performance-based code system will be the harmonization between the FSE concepts and the grading system. Originally some of the currently available analytical flame spread models intended to use data from heat release tests such as the ISO5660 Cone Calorimeter as the input[14,15], and have potential capability for the application to the classification. Several works in the 1990s have tried to explain the results of the ISO 9705 Room Corner Test, a full scale test on lining fires, from the asymptotic flame spread behavior

predicted by analytical models with the data from the ISO 5660 and other bench-scale tests.

Figure 2(a) is a graphical representation[10] of the asymptotic behaviors of the flame spread predicted from a simple analytical equation for concurrent flame spread first derived by Saito, Quintiere and Williams(the SQW equation, see equation(2))[8] and solved analytically by Thomas and Karlsson[9]. The SQW equation and its variations essentially represent flame spread velocity by the distance between the flame front and the pyrolysis front divided by the characteristic time to ignition, i.e. $V_p = (x_f - x_p)/\tau$. This formulation assumes a uniform flame heating between the flame front and the pyrolysis front and the simultaneous ignition over this area after the characteristic ignition time τ. τ is taken as constant in a stationary flame spread and can be represented by the time to ignition under the flame heat flux level. The SQW equation also employs a linearized flame length approximation, i.e. $x_f = L_f = KQ$ where Q is the total heat release rate per unit width of the pyrolysis zone, whilst experiments suggest a weaker power dependence, e.g. $x_f = L_f \propto Q^{2/3}$, for upward flame spread[8]. From experimental flame length correlations, K is believed to be around 0.01 - 0.02 for a [10^{-1}] - [10^{1}] m tall flame. The SQW equation has been generalized to incorporate the burnout effect[16], and the power dependence of the flame length[17,18]. While these improvements generally tend to make an analytical treatment rather difficult, the present paper tries to use only analytical treatment. The solution in Figure 2(a) assumes further a charring material, whose time history of heat release rate is represented by an exponential decay function, $q(t) = q_{max} \exp(-t/t_b)$. The solution can be divided into the following three categories according to its asymptotic behavior. Flame spreading velocity diverges in the region I, is accelerated at the beginning but is gradually decelerated and finally diminishes in the region II. Flame spread is decelerated from the beginning and will die out in the region III. Lining materials falling into the region I is believed to cause flashover, and those falling into the region II may cause flashover in a small enclosure compared with the fire source. A room fire should not reach flashover with any lining material in the region III, unless the fire source is large enough. For a heat release rate represented by a rectangular function of time, $q(t) = q_{max}\{1 - U(t - t_b)\}$, it has been found that the qualitative behavior of the solution can be divided into only two categories as seen in Figure 2(b)[16]. In this figure, the acceleration/deceleration criterion, $\tau/t_b = Kq_{max} - 1$, also stands for the divergence/convergence criterion. Through a different analysis, Quintiere derived an acceleration/deceleration criterion for the local heat release rate represented by a rectangular function[19]. This criterion is essentially equivalent with the acceleration/ deceleration boundary in Figure 2(b). He further demonstrated that his criterion can predict whether flashover occur in the first ten minutes in the ISO 9705 Room Corner test.

There are some criticisms against this approach from practitioners; use of not highly reproducible material properties, possible influence of subjective judgment in the approximation of the heat release rate by a simple function and the use of a small specimen to obtain the input data have been pointed out. A safer side approximation of the test data may resolve the first two criticism, but it may spoil the benefit of the prediction-based classification. The second criticism is rather directed to the use of bench scale tests for the evaluation of a large building product. Certainly complicated surface treatment, ribs, cavities and other construction details may not be represented in a 10 cm square specimen to be used for the Cone Calorimeter. Probably those lining materials featuring such complicated construction details need essentially an intermediate or large scale test. Also the basic assumption for the SQW equation has been found to be valid for only limited conditions[16,20], and there is some theoretical doubt in the validity of the analytical solution if it is far from the steady state. However, as long as the analytical approach is applied only for the evaluation of asymptotic flame spread behaviors, this approach should still be effective as there is no direct need to use its solution in such a qualitative evaluation.

CLASSIFICATION OF THE FLAME SPREAD BEHAVIOR

An attempt has been made to resolve such difficulty of the analytical approach. In order to derive a rational classification using row test data, analysis has been made on the generalized SQW equation:

$$V_p(t) = (x_f - x_p)/\tau = [K[Q_o(t)\{1-U(t-t_b)\}\} + x_{po}q(t) + \int_0^t q(t-\xi)V_p(\xi)d\xi] + \{\int_0^{t-t_b} V_p(\xi)d\xi + x_{po}\}U(t-t_b) - \{x_{po} + \int_0^t V_p(\xi)d\xi\}]/\tau \quad (1)$$

The generalized SQW equation is a generalization of the SQW equation to incorporate the burnout effect[16]. For $t<t_b$, equation(1) can be simplified into the original SQW equation as

$$V_p(t) = [K[Q_o(t) + x_{po}q(t) + \int_0^t q(t-\xi)V_p(\xi)d\xi] - \{x_{po} + \int_0^t V_p(\xi)d\xi\}]/\tau$$
$$= [K\,Q_o(t) + x_{po}\{K\,q(t) - 1\} + \int_0^t \{K\,q(t-\xi) - 1\}V_p(\xi)d\xi]/\tau \quad (2)$$

Once the fire source is removed or extinguished, the fire source term $Q_o(t)$ disappears and equation(2) further becomes

$$V_p(t) = [\,x_{po}\{K\,q(t) - 1\} + \int_0^t \{K\,q(t-\xi) - 1\}V_p(\xi)d\xi]/\tau \quad (3)$$

Flame spread is sustained only when $V_p(t)>0$; equation(3) suggests that if $Kq(t) \geqq 1$ the flame spread can be sustained and if $Kq_{max} <1$ the flame spread should be terminated after the removal of the fire source. A "lining material that may ignite in fire but cannot sustain flame spread without the fire source" has a clear implication for fire safety, and this condition can be identified by judging if its heat release rate data satisfies $Kq_{max} <1$.

One deficit of $Kq_{max} <1$ for practical fire safety assessment is perhaps the use of the peak heat release rate, q_{max}, which, according to testing practice, is believed not to be very reproducible for its high sensitivity to the sampling interval and other reasons. Taking burnout into account, the following condition, weaker than $Kq_{max} <1$,

$$\int_0^{t_b} Kq(\xi)\,d\xi\,/\,t_b < 1 \quad (4)$$

is likely to assure a similar criterion for practical lining materials for the sustainability of flame spread. Equation(4) needs determination of burnout time,$t>t_b$, and total heat release rate, $\int_0^{t_b} q(\xi)d\xi$, both of which are less sensitive to measurement apparatus and protocol than q_{max} and are more reproducible than q_{max}. Effectiveness of this criterion can be demonstrated as follows.

For $t>t_b$, equation(1) yields

$$V_p(t) = \int_{-t_b} \{Kq(t-\xi) - 1\}\,V_p(\xi)d\xi\,/\,\tau = \int_0^{t_b} \{Kq(\xi) - 1\}\,V_p(t-\xi)d\xi\,/\,\tau \quad (5)$$

Even if the flame spread velocity is positive, flame spread will be gradually decelerated and finally die out if $dV_p(t)/dt<0$. The condition for $dV_p(t)/dt<0$ can be obtained by taking the limit for a stationary flame spread from equation(5). Assuming $V_p(t)=constant$, equation(5) yields

$$\int_0^{t_b} Kq(\xi)d\xi\,/\,t_b - 1 = \tau\,/\,t_b \quad (6)$$

This condition is the divide between the accelerated and the decelerated modes of flame spread, and if the left hand side of equation(6) is smaller than the right hand side, τ / t_b, the flame spread is believed to be always decelerated. If furthermore the left hand side of equation(6) is negative, namely $\int_0^{t_b} Kq(\xi)\, d\xi / t_b < 1$, equation(5) suggests that positive value of V_p can be achieved only when $q(t)$ is an increasing function of time with its peak just before the burnout large enough to compensate the decrease of flame spread velocity with time. Obviously such functional form of $q(t)$ should be hardly consistent with equation(4) which specifies an upper limit of the total heat release rate. In various practical combustible lining materials, charring materials have normally the peak heat release rate slightly after the ignition, and there is virtually no lining material that has a significant peak at the end of surface burning while heat release rate of some noncharring materials such as PMMA is represented by a weakly increasing function of time. From these discussions, a lining material satisfying $\int_0^{t_b} Kq(\xi)\, d\xi / t_b < 1$ is believed to be unable to sustain flame spread once the surface burning is isolated from fire source by its removal or burnout of the surface burning. In that sense, this condition gives a strong limitation for the flame spread, and materials satisfying this condition can be referred to as "strongly self-extinguishable" materials.

Another characterization of burning behavior can be introduced for those materials that may sustain flame spread but cannot cause any accelerated flame spread. From equation(6), this condition can be represented as

$$\int_0^{t_b} Kq(\xi) d\xi / t_b - 1 < \tau / t_b \qquad (7)$$

Although this condition allows some larger fire development than the previous criteria, fire is expected to extinguish automatically, and those materials satisfying equation(7) may be referred to as "weakly self-extinguishable" materials.

The strongly and weakly self-extinguishable materials can be illustrated graphically as seen in Figure 3. The first term of the left hand side of equation(6) is equivalent to Kq_{max} for those materials whose dynamic heat release rate is represented either by an exponential or a rectangular function. The equation(6) is equivalent to the criticality, $\tau / t_b = Kq_{max} - 1$, in Figure 2 for these simple analytical solutions if, for an exponential function, the time constant representing the decay is used for t_b. In that sense, Figure 3 is a generalization of the Figures 2(a) and (b). Also, for heat release rate represented as a rectangular function, equation(6) becomes equivalent with the criteria that Quintiere[19] has derived for the classification of lining materials in terms of the time to flashover. It is important that all material properties included in the critical conditions for both the strongly and weakly extinguishable materials can be obtained directly with a material test to measure dynamic heat release rate such as the Cone Calorimeter, total heat release rate, time to ignition and the burnout time.

CORRELATION BETWEEN CONE CALORIMETER AND ROOM CORNER TEST

Various lining materials were tested against the Cone Calorimeter and the ISO 9705 Room Corner Test within the recently completed MoC R & D program on fire test methods. Table 1 is a summary of the specimens, material description and main results of the Cone Calorimeter(50kW/m2) and the ISO 9705 Room Corner Test. Although the number of materials was limited, the tested materials cover wide range of fire performance from *noncombustible materials* to those not rated as *fire protective materials* in the Building Standard Law. $K=0.02$ was assumed experimental flame height correlations on the similar range of flame height from the ignition source with the ISO 9705 Room Corner Test. Since

time to burnout was not easy to identify visually for a few materials, the time to the heat release rate decaying to 20kW/m^2 was defined as the time to burnout. This definition seemed to be consistent with visual definition for most of specimens with which the visual identification of burnout was easy. For the calculation of t_b, similar definition, q=, 20kW/m^2 was used for the identification of the initiation of flaming. This simple definition led to minor difference with the visual definition of time to ignition as seen in Table 4. Classifying the ISO 9705 Room Corner Test results into four grades according to the time to flashover, i.e. no flashover, flashover between 10 and 20 minutes, flashover between 5 and 10 minutes and flashover before 5 minutes, the results from the Cone Calorimeter and the ISO 9705 Room Corner Test are correlated, according to the discussion in the previous section, as shown in Figure 4.

Table 1 also summarizes F values, a dimensionless index defined as

$$F = \tau / \{ \int_0^{t_b} Kq(\xi) d\xi - t_b \} \tag{8}$$

for each specimen. F is negative for strongly self-extinguishable materials, and larger than unity for weakly self-extinguishable materials. Table 4 suggests a promising prospect that F could be an index for practical prediction of the range of time to flashover at the ISO 9705 Room Corner Test; for $0 < F < 0.15$, flashover is likely to occur in 5 minutes from ignition, for $0.15 < F < 0.44$, flashover may occur between 5 and 10 minutes. Although clear flashover did not occur with the rest of F value range, unsustained flame projection from the doorway was observed for materials 7A0 and 8B with which average F value was between 1.1~1.8. Especially peak heat release rate for 7A0 at the ISO 9705 Room Corner Test exceeded 1000kW. If these are to be eliminated, $F > 2$ could be a condition for flashover not to occur at the ISO 9705 Room Corner Test. Also no flashover was observed with the two materials with $F < 0$. Use of K value still smaller than 0.02 may lead to a better correlation between the Cone Calorimeter and the ISO9705 Room Corner Test.

CONCLUDING REMARKS

As long as the ISO 9705 Room Corner Test is used as the reference for the fire safety assessment of lining materials, the analytical approach has a promising prospect to serve as a practical tool to classify the lining materials. The 2.4m x 3.6m room of the ISO9705 Room Corner Test represents a minimum room size in buildings, and the development of a lining fire should be faster than in a larger and commoner room. The practically sole domination of the results of the Room Corner Test by the concurrent flame spread may be partly because of the use of a very small enclosure in the Room Corner Test. Role of the downward flame spread along the enclosure boundaries can become more important in a larger compartment. Development of mathematical room fire models[e.g.21,22] is believed to be important for the better understanding of fire behavior in larger compartments.

TERMINOLOGY

$U(t)$: Heaviside's unit function
q :heat release rate per unit area
t : time
L_f : flame length
x_p : location of pyrolysis front
Q : heat release rate per unit width
Q_o : heat release rate of the ignition source
V_p : flame spread velocity
K : constant(L_f/Q)
t_b : time to burnout
x_f : location of flame front
x_{po} : pilot flame height
τ :characteristic time to ignition

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Table 1 Materials and Summary Test Results of Cone Calorimeter and ISO9705 Room Corner Test

Specimen	Material	Time to ignition* (s)	Time to burnout* (s)	tb (s)	Time to ignition** τ (s)	Total heat release (kJ/m²)	$\int q''(t)dt/tb$ (kW/m²)	τ/tb (-)	F value (-)	ISO9705 Time to Flashover (min)	Class
7A0-1	Wall paper(PVC 300g/m²) on gypsumboard BSL rating QNC	14	58	44	16	2626	57.14	0.36	2.57	Unsustained flame projection at 10.3 min	1/2
7A0-2		12	58	46	9	2703	56.59	0.2	1.54		
7A0-3		14	56	42	10	2546	58.48	0.24	1.41		
7A1-1	Wall paper(PVC 500g/m²) on gypsumboard BSL rating FR	14	76	62	9	4814	76.34	0.15	0.28	11.1	2
7A1-2		10	70	60	9	4765	78.57	0.15	0.26		
7A1-3		10	70	60	7	4765	78.57	0.12	0.21		
7F1-1	Polyisocyanulate + gypsumboard BSL rating -	4	72	68	2	5228	76.09	0.03	0.06	0.73	4
7F1-2		22	74	52	2	3415	63.69	0.04	0.15		
7F1-3		18	72	54	2	4057	72.48	0.04	0.09		
7G-1	FR plywood BSL rating FR	16	600	584	22	50022	85.59	0.04	0.06	4.5	4
7G-2		20	600	580	19	58443	100.59	0.03	0.03		
7G-3		24	600	576	24	47393	82.21	0.04	0.06		
7Q-1	Soft fiberboard BSL rating -	11	467	456	8	32453	71.14	0.02	0.05	not conducted for safety reason	4
7Q-2		9	502	493	7	33712	68.37	0.01	0.03		
7Q-3		9	506	497	7	34410	69.22	0.01	0.03		
8A-1	Wall paper(FR cloth 700g/m²) on gypsumboard BSL rating FR	34	176	142	36	5960	40.56	0.25	-1.32	NO FO	1
8A-2		36	184	148	40	6760	43.88	0.27	-2.25		
8A-3		36	178	142	35	5644	38.28	0.25	-1.09		
8B-1	Wall paper(FR cloth 300g/m²) on gypsumboard BSL rating QNC	27	109	82	23	5648	67.37	0.28	0.8	Unsustained flame projection at 10.3 min	1/2
8B-2		27	111	84	24	5255	60.46	0.29	1.38		
8B-3		27	105	78	24	5020	62.12	0.31	1.29		
8C-1	Emulsion paint +gypsumboard BSL rating QNC	52	72	20	49	2233	100.35	2.45	2.43	NO FO	1
8C-2		56	74	18	53	2062	108.06	2.94	2.53		
8C-3		66	84	18	64	1961	100.78	3.56	3.49		
8D-1	Acrylic paint+gypsumboard BSL rating QNC	31	67	36	26	3186	83.89	0.72	1.06	NO FO	1
8D-2		35	71	36	31	3009	79.75	0.86	1.43		
8D-3		33	69	36	30	2974	77.36	0.83	1.51		
8E-1	Emulsion paint (70g/m²)+gypsumboard BSL rating NC	38	60	22	35	2652	113	1.59	1.26	NO FO	1
8E-2		44	62	18	41	2456	133.67	2.28	1.37		
8E-3		48	66	18	45	2423	128.11	2.5	1.6		
8F-1	Emulsion paint (111g/m²)+gypsumboard BSL rating NC	47	99	52	41	5606	104.35	0.79	0.72	NO FO	1
8F-2		43	93	50	36	5164	98.6	0.72	0.74		
8F-3		45	95	50	39	5415	104.96	0.78	0.71		
8K-1	Wall paper (PVC 300g/m²) +gypsumboard BSL rating QNC	38	64	26	14	1479	40.5	0.54	-2.84	NO FO	1
8K-2		6	94	88	15	2959	32.9	0.17	-0.5		
8K-3		10	52	42	16	2167	48.5	0.38	-12.67		
10C-1	FR plywood	124	600	476	124	32336	67.49	0.26	0.74		
10C-2		132	600	468	132	28604	60.5	0.28	1.33		
10C-3		136	600	464	136	30736	65.37	0.29	0.94		
10D-1	Composite: Aluminum +Polyethylene+Aluminum	220	664	444	220	47990	106.68	0.5	0.44	7.0	3
10D-2		216	756	540	210	70901	130.05	0.39	0.24		
10D-3		216	756	540	210	70901	130.05	0.39	0.24		

BSL rating: NC=*Noncombustible material*. QNC=*Quasi-noncombustible material*. FR=*Fire retardant material*.

* defined from heat release rate assuming q''=20kW/m² for the start and termination of flaming

** defined from visual observation according to ISO5660 and Cone Calorimeter protocols.

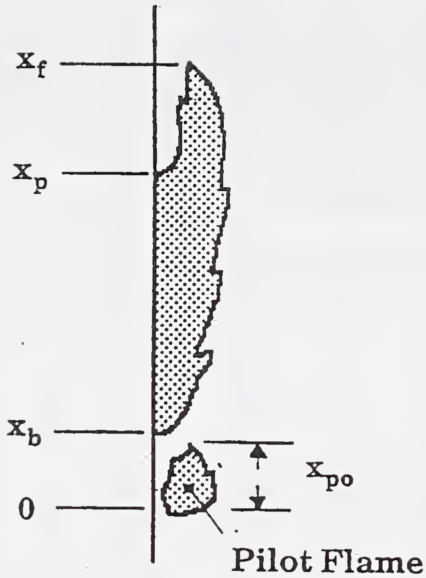
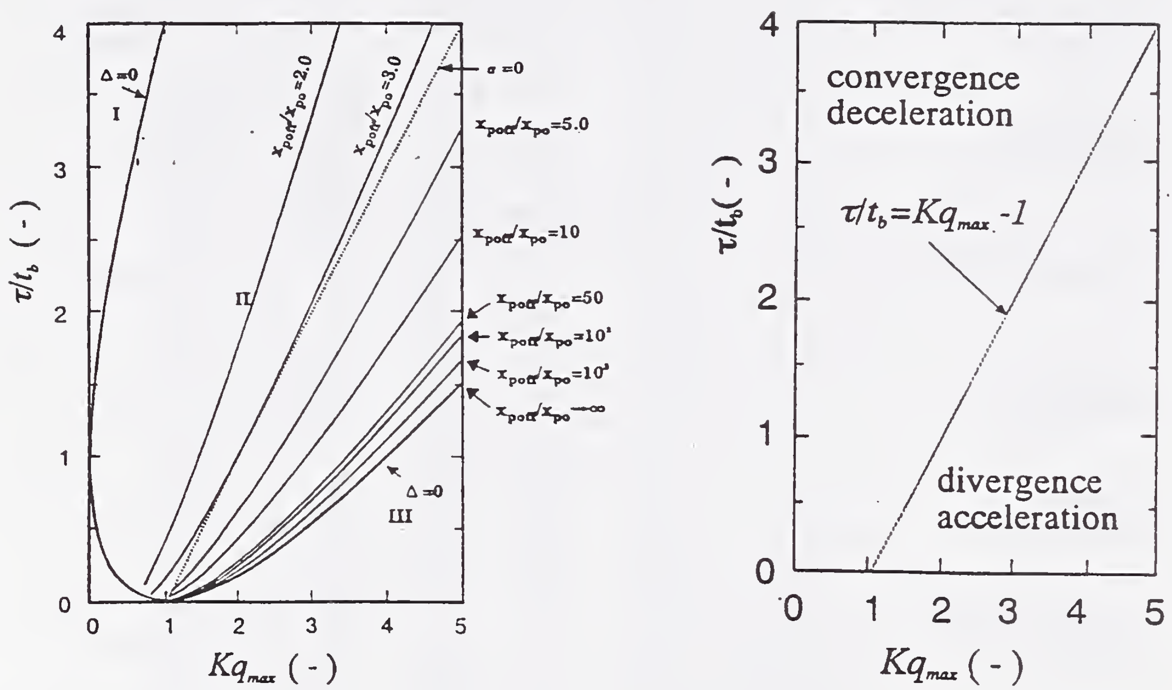


Figure 1 Wall Flame Spread, Schematic Diagram



(a) Charring materials, sustained pilot flame
$q(t) = q_{max} \, exp(-t/t_b)$

(b) Non-charrig materials
$q(t) = q_{max}\{1 - U(t - t_b)\}$

Figure 2 Asymptotic Behaviors of Concurrent Flame Spread

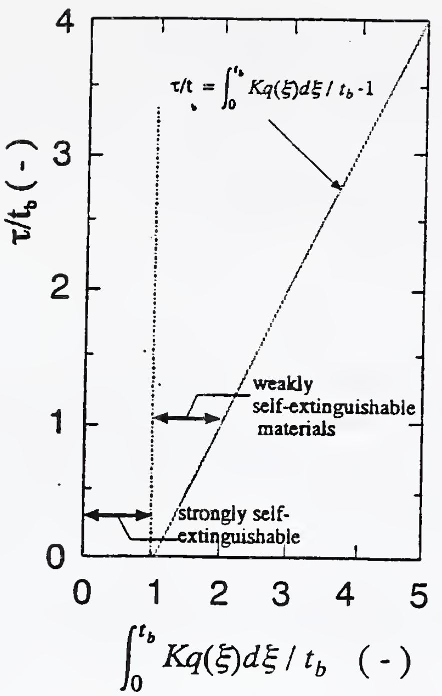


Figure 3 Classification of Asymptotic flame spread behaviors by row heat release data

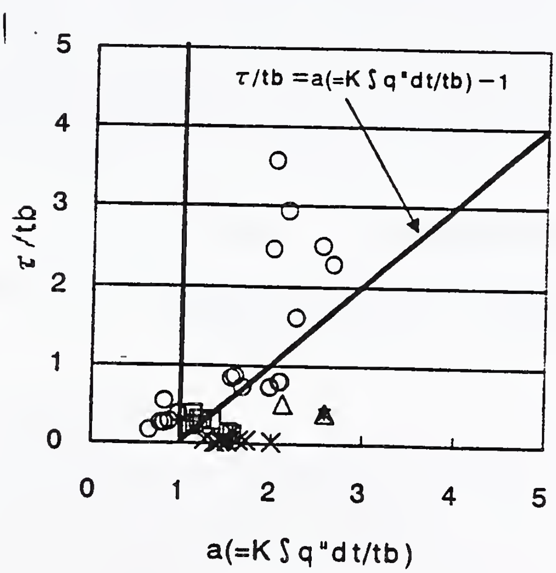


Figure 4 Correlation between the time to flashover in ISO9705 Room Corner Test and heat release characteristics at heat flux level 50kW/m² in the Cone Calorimeter

FORMULAS FOR FIRE GROWTH PHENOMENA BASED ON MATERIAL PROPERTIES

James G. Quintiere
Department of Fire Protection Engineering
University of Maryland
College Park, MD 20742

ABSTRACT

A review is presented of research conducted over the past decade to investigate models to predict material fire behavior. All of the models discussed are presented by analytical formulas derived to maintain what are believed to be the dominant phenomena. Ignition is based on an inert material with a fixed ignition temperature. Non-linear radiation effects are included. Expressions for the burning rate of non-charring and charring materials based on data from the Cone Calorimeter are given. The models are based on immediate conversion of solid fuel to fuel vapor and char, and on constant thermal properties and char fraction. A general formula for flame spread results in a correlation for flashover time in the ISO 9705 Room-Corner Test. The material properties needed, and their derivation is discussed. The level of accuracy of results show the practicality of this type of approach.

INTRODUCTION

The evaluation of the fire hazard of materials has been a challenging task that is based in empirical testing and a wide variety of regulatory practices. There is not a uniquely accepted technical consensus on how to approach this problem. Over about the last decade, we have investigated the feasibility of using the minimum amount of mechanisms in the formulation of analytical formulas to evaluate the various aspects of material fire behavior, namely: ignition, burning rate, flame spread and fire growth. Each fire process contributes new essential mechanisms, and therefore new properties that are needed in the formula. These properties, although modelling based, must have some universality or they are merely fitting parameters. The real answer for these "equivalent material properties" lies somewhere between meaningful science and mathematical coefficients.

Table 1. Material properties and Fire Process

PROCESSES→ PROPERTIES↓	Ignition	Flame Spread	Burning Rate Non-charring	Burning Rate Charring
Ignition, Vaporization Temperature	x	x	x	x
Thermal Properties, original material	x	x	x	x
Heat of Gasification	--	--	x	x
Char Properties	--	--	--	x
Flame Heat Flux, Length	--	x	x	x

For material properties to be practical in fire modeling they must not only produce accurate predictions, but they must be unambiguously deduced from test data. Keeping the number of properties to a minimum is also desirable. Since ignition precedes flame spread and burning, its properties feed into the latter two processes. The hierarchy of material properties with phenomena is shown in Table 1, and the relationship between phenomena and properties is implied by "x". We shall discuss these relationships and their basis in formulas for the processes.

IGNITION

The simplest model for *piloted ignition* that can be rendered is that based purely on heat conduction. We shall consider the case of a *thermally thick solid* exposed to a constant incident heat flux, $\dot{q}_i''$, under convective and radiative cooling to a fixed temperature ambient at T_∞. Assumptions of the model include:

1. inert semi-infinite solid with constant thermal properties, $k\rho c$,
2. constant ignition temperature, T_{ig}, and
3. blackbody surface conditions.

Assumption 1 requires minimal effect of energy sinks due to phase change and pyrolysis processes. To the extent these energy effects are important, they would be absorbed into an *effective kρc property*. Assumption 2 requires the same evolution of fuel gases at T_{ig} to always cause the lower flammable limit to occur at the pilot ignition source in a small time. Ideally, the pyrolysis kinetics must be very fast along with the time for mixing between the gaseous fuel and the air. Pyrolysis may play a significant role at low heat flux conditions near the critical flux for ignition, $\dot{q}_{cr}''$.

Since this problem is non-linear due to the radiation boundary condition, an exact analytical solution is not possible. An approximate integral solution yields the following dimensionless analytical solution for the time to ignite[1]:

$$\tau_{ig} = C\left(\frac{\dot{q}_{cr}''}{\dot{q}_i''}\right)^2 \qquad (1)$$

$$\text{where } \tau_{ig} = \left(\frac{\dot{q}_{cr}''}{T_{ig} - T_\infty}\right)^2 \frac{t_{ig}}{k\rho c} \qquad (1a)$$

$$\dot{q}_{cr}'' = \sigma\left(T_{ig}^4 - T_\infty^4\right) + h_c\left(T_{ig} - T_\infty\right) \qquad (1b)$$

$$\text{and } C = \frac{\pi/2}{(2-\beta)(1-\beta)},\ \beta = \frac{\dot{q}_{cr}''}{\dot{q}_i''}. \qquad (1c)$$

The coefficient, C, was modified by replacing 4/3 of the integral solution with $\pi/2$ so as to match the exact solution for purely convective heat loss. The exact solution for purely convective heat loss is

$$\frac{\dot{q}_{cr}''}{\dot{q}_i''} = 1 - e^{\tau_{ig}}\operatorname{erfc}\sqrt{\tau_{ig}} \to 2\sqrt{\tau_{ig}/\pi} \text{ as } \tau_{ig} \text{ becomes small.} \qquad (2)$$

For the high flux limit or small time limit, both Eqns (1) and (2) give the well known limit where C is $\pi/2$. Approximate solutions to the non-linear problem have also been given for the purely radiative heat loss case by Delichatsios et al. [2]. Their linearized results are

$$\frac{1}{\sqrt{\tau_{ig}}}=\sqrt{\pi}\left(\frac{\dot{q}_i''}{\dot{q}_{cr}''}-1\right),\ \text{for}\ \frac{\dot{q}_i''}{\dot{q}_{cr}''}\le 1.1 \tag{3a}$$

$$\frac{1}{\sqrt{\tau_{ig}}}=\frac{2}{\sqrt{\pi}}\left(\frac{\dot{q}_i''}{\dot{q}_{cr}''}-0.64\right),\ \text{for}\ \frac{\dot{q}_i''}{\dot{q}_{cr}''}\ge 3.0. \tag{3b}$$

Eq. (1) can also be put in the same form as Eq (3b) for $\dot{q}_i''/\dot{q}_{cr}''\ge 2$ with the intercept of 0.64 replaced by 0.76, and for Eq. (2) the intercept replaced as 0.80. Figure 1 shows a comparison of

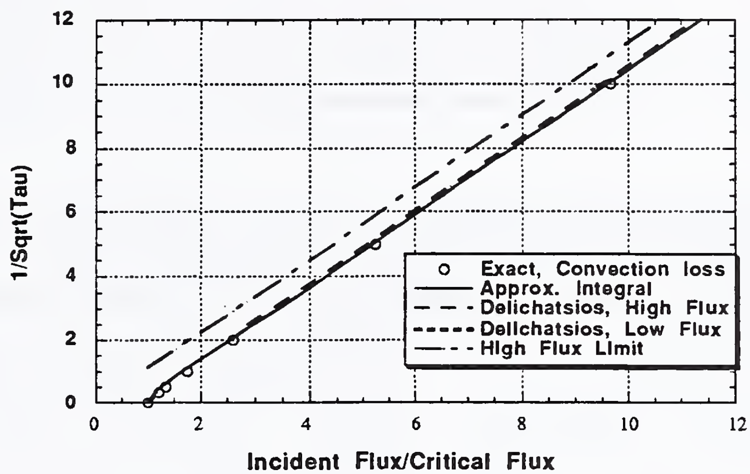


Figure 1. Comparison of Ignition Solutions

these solutions, and demonstrates the accuracy of Eq. (1). The more simple limit solution with C as $\pi/2$ under-predicts the dimensionless time as the dimensionless heat flux decreases toward 1. The limit solution might give an acceptable estimate for $\dot{q}_i''/\dot{q}_{cr}''\ge 2$ where $t_{ig,limit}/t_{ig}$ ranges from about 0.5 to 1.

Any of these equations offer a means to compare experimental data. They can also be used to fit experimental data by appropriately selecting the material properties: $k\rho c$ and T_{ig}. However, there can be operational difficulties in implementing this property derivation since the simple conduction theory may not always apply. A plot of the ignition data in the form of $t_{ig}^{-1/2}$ versus $\dot{q}_i''$ offers a means to determine the critical heat flux from the intercept on the x-axis by using Eq. (3b), T_{ig} from Eq. (1b), and $k\rho c$ from the slope of the graph. Since the slope depends on $(T_{ig}-T_\infty)\sqrt{k\rho c}$, any inaccuracy in determining $\dot{q}_{cr}''$ affects T_{ig} and therefore $k\rho c$, accordingly. Figure 2 gives an example of a dimensionless plot of ignition data for a variety of wood species, and the tightness of the data to a linear fit following the theory shows the appropriateness of the derived properties and the theory. Table 2 shows the derived wood properties.

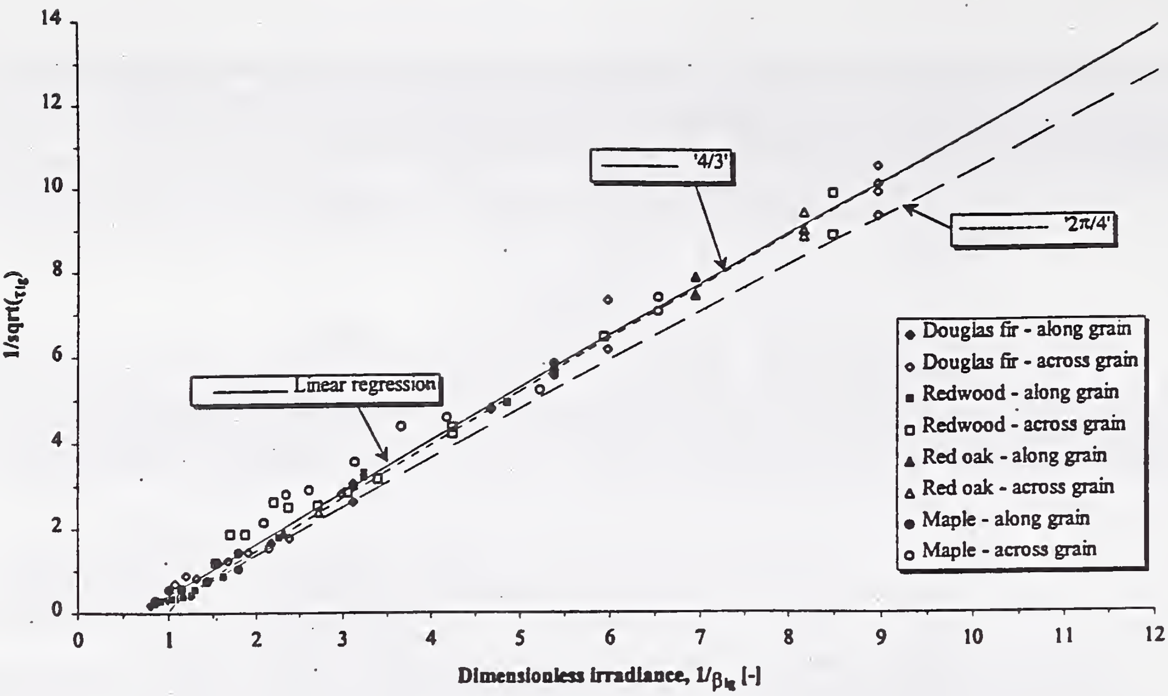


Figure 2. A comparison of dimensionless ignition data for wood species with the integral theory.

Table 2. Derived Material Properties [1,5]

Material	ρ kg/m³	T_{ig} °C	kρc $kJ^2m^{-4}K^{-2}s^{-1}$	Δh_c kJ/g	L kJ/g_{lost}	L_o kJ/g_{orig}	Char Fraction,ϕ –	Cone Flame Heat Flux kW/m²
Redwood,L*	354	375	0.22	11.9	9.4	2.83	0.12-0.41	35
Redwood, X*	328	204	2.07	9.0	7.5	3.18	0.17-0.45	33
Douglas fir,L	502	384	0.25	11.0	12.5	1.57	0.27-0.62	17
Douglas fir,X	455	258	1.44	9.1	6.8	2.93	0.16-0.42	46
Red oak,L	753	304	1.01	12.3	10.0	2.34	0.21-0.49	35
Red oak,X	678	275	1.88	12.1	4.5	2.83	0.00-0.39	33
Maple,L	741	354	0.67	13.0	4.4	1.70	0.41-0.71	16
Maple,X	742	150	11.0	12.1	6.3	3.53	0.06-0.39	46
PMMA(Plycst)	1190	180+	2.1	--	2.8	2.8	0	37
Nylon	1169	380+	0.87	--	3.8	3.8	0	30
Polyethylene	955	300+	1.8	--	3.6	3.6	0	25
Polypropylene	900	210+	2.2	--	3.1	3.1	0	14

L, cut along the grain; X, cut across the grain; +, underestimated.

BURNING RATE

The simplest model to represent the mass loss rate of a solid due to an incident heat flux is to consider it as a steady state evaporating liquid at an original temperature, T_∞. For this idealization, the mass loss rate per unit area, $\dot{m}''$, is given in terms of the net heat flux, $\dot{q}''$, as

$$\dot{m}'' = \dot{q}'' / L \tag{4}$$

where L is the heat of gasification given as the sum of the heat of vaporization, ΔH_v, and the sensible energy needed to bring the solid fuel from its original temperature to its vaporization temperature, T_v, i.e.

$$L = \Delta H_v + c(T_v - T_\infty). \tag{5}$$

As long the solid fuel will vaporize without leaving a char residue, there is relatively no ambiguity on how to define L as a material property. For a charring material, an appropriate definition for L to obtain mass *loss* rate might be taken as

$$L = L_o/(1-\phi) \text{ in kJ/g fuel lost} \tag{6}$$

where L_o is based on the original mass of material as given by Eq. (5), and ϕ is the char fraction. Table 2 gives some typical results for L and L_o and shows the effect of the char fraction giving $L>L_o$ for a given polymer. A solution which tries to take into account the transient burning behavior, is more complex, especially for a charring material.

The transient solution is found from an approximate integral model based on studies we conducted [1,3-5] and is nearly identical to a formulation by Moghtaderi et al. [6]. The approximate solution has been shown to be in good agreement with more exact numerical solutions for the same equations. Therefore, the integral solution offers the prospect for analytical results to more clearly display the importance of properties and variables needed. The specific transient burning rate problem considered is a thermally thick solid with a constant incident heat flux composed of external radiative and flame components. The problem addresses the initial preheating up to ignition, and the potential development of a char layer. The significant modeling assumptions include:

1. the ignition temperature is the vaporization temperature,
2. the solid vaporizes at a fixed temperature with a constant heat of vaporization, ΔH_v,
3. the flame heat flux and the char fraction are constant, and
4. all thermal properties are constant.

The integral solution is described below:

The net heat flux to the surface for the burning problem is given as

$$\dot{q}'' = \dot{q}''_- \equiv \dot{q}''_i - \sigma(T_{ig}^4 - T_\infty^4) - h_c(T_{ig} - T_\infty),\ t \le t_{ig} \tag{7a}$$

$$\dot{q}'' = \dot{q}''_+ \equiv \dot{q}''_i - \sigma(T_{ig}^4 - T_\infty^4) + \dot{q}''_f,\ \ t \ge t_{ig} \tag{7b}$$

where $\dot{q}''_f$ is the total flame heat flux. This step change in heat flux produces a step change in the mass loss rate of the model when combustion occurs. This modeling approximation produces an instantaneous burning rate when the flame appears, and is given as

$$\dot{m}''_{ig} = \frac{(1-\phi)}{\Delta H_v}\left(\dot{q}''_f + h_c(T_{ig} - T_\infty)\right). \tag{8}$$

Non-Charring Result (ϕ=0)

The transient non-charring burning rate can be given as [5]:

$$\frac{\dot{m}''L}{(1-\phi)\dot{q}''_{+}} = \left(\frac{L}{\Delta H_v}\right)\left(1 - \frac{c(T_{ig}-T_{\infty})}{L}\left(\frac{1}{\Delta}\right)\right) \tag{9}$$

with

$$\frac{1-\Delta}{1-\Delta_{ig}} = \exp\left(-(\Delta-\Delta_{ig}) - 6\left(\frac{L}{\Delta H_v}\right)(\tau-\tau_{ig})\right)$$

where here $\tau \equiv \frac{\left(\frac{k}{\rho c}\right)t}{\delta_s^2}$ is a dimensionless time, and

$\delta_s \equiv \frac{2kL}{c\dot{q}''_{+}}$ is a thermal conduction length needed to achieve steady vaporization.

Δ is a dimensionless thermal length, δ/δ_s, and Δ_{ig} is its value at ignition.

At steady state Δ=1, and the left-hand-side of Eq. (9) is also equal to 1. Table 2 gives the values of L for several non-charring plastics derived from steady state data indicative of Figure 3. In addition to the ignition derived properties, specific heat information is also needed and was selected from the literature. Figures 4a and 4b show typical predictions of transient burning compared to measured data in the Cone Calorimeter. Table 2 also gives needed corresponding values for the flame heat flux in the Cone heater for horizontal burning.

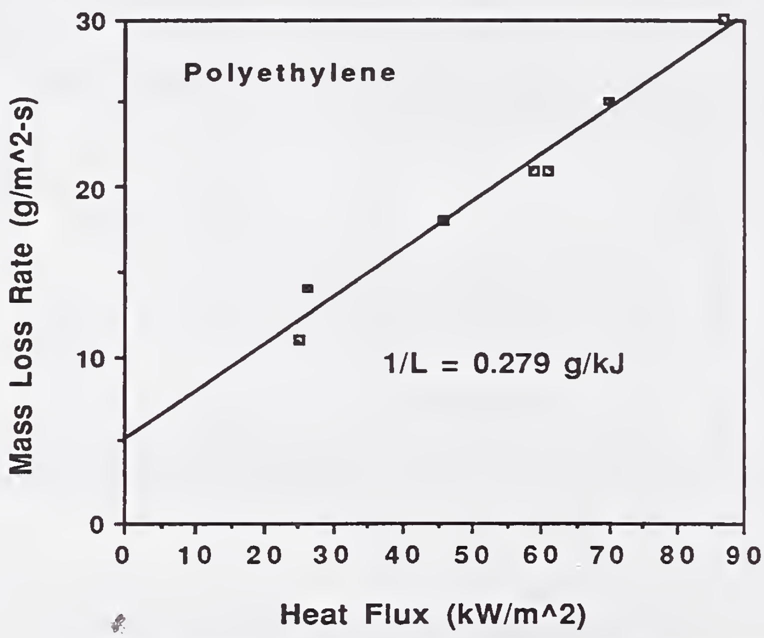


Figure 3. Steady mass loss rate for polyethylene [5].

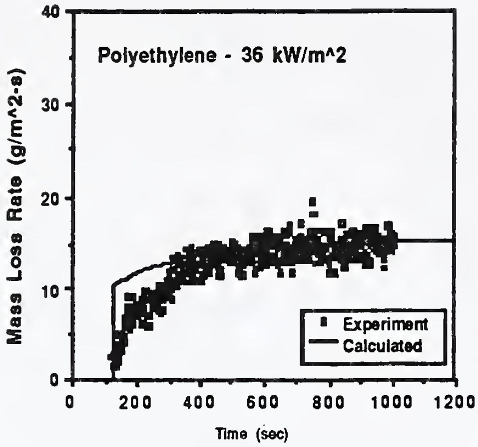


Figure 4a. PE in Cone Cal. At 36 kW/m2.

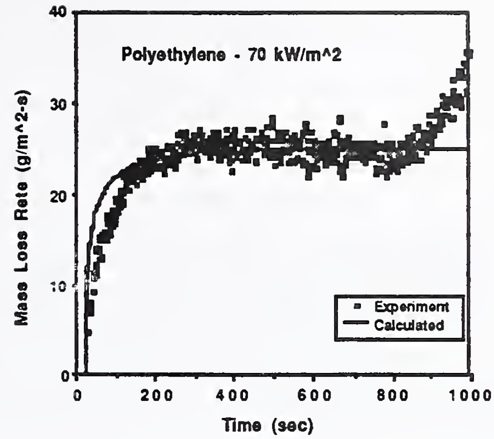


Figure 4a. PE in Cone Cal. At 70 kW/m2.

Charring Result

The corresponding equations that arise from an approximate integral solution are highly nonlinear, and an analytical solution is not directly possible. However, approximate analytical solutions can be produced for small and large time, and their combination produce reasonable results (Fig 5). The solutions are summarized below:

Small Time: The small time charring result follows the non-charring case with a given ϕ up to a peak burning rate after which the long time solution begins. The short time burning rate solution is given from Eq. (9) as

$$\frac{\dot{m}'' L_o}{(1-\phi)\dot{q}''_+} = \left(\frac{L_o}{\Delta H_v}\right)\left(1 - \frac{c(T_{ig} - T_\infty)}{L_o}\left(\frac{1}{\Delta}\right)\right) \tag{10}$$

$$\text{where } \Delta \approx \Delta_{ig} + 6\left(\frac{L_o}{\Delta H_v}\right)\left(1-\Delta_{ig}\right)\left(\tau - \tau_{ig}\right).$$

It can be shown that the char depth is initially linear in time and in heat flux:

$$\delta_c \approx \frac{\dot{q}''_f}{\rho \Delta H_v}\left(1 - \frac{\dot{q}''_-}{\dot{q}''_+}\right)\left(t - t_{ig}\right). \tag{11}$$

The surface temperature, $T_s \approx T_{ig}$.

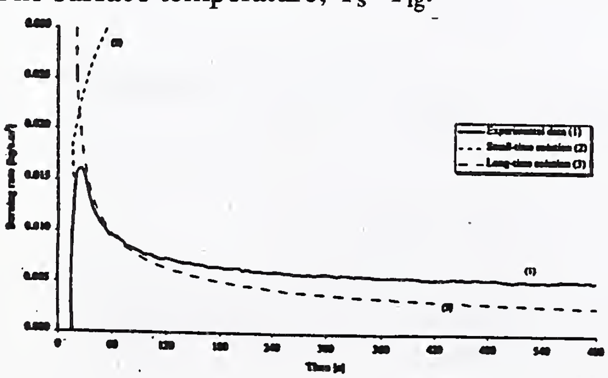


Figure 5a. Burn Rate for Douglas fir

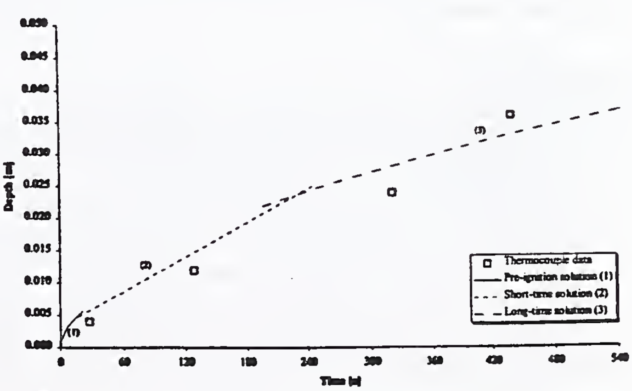


Figure 5b. Thermal depth, Douglas fir

<u>Large Time:</u> The long time solution is given as follows:

$$\delta_c \approx \sqrt{\frac{2k_c(T_s - T_{ig})(t - t_{ig})}{\rho \Delta H_v}} \tag{12}$$

$$\dot{m}'' = (1-\phi)\rho \frac{d\delta_c}{dt} \approx (1-\phi)\sqrt{\frac{\rho k_c (T_s - T_{ig})}{2\Delta H_v (t - t_{ig})}}, \tag{13}$$

and

$$T_s \approx \frac{\left(\dot{q}_f'' + \dot{q}_i''\right)^{1/4}}{\sigma}. \tag{14}$$

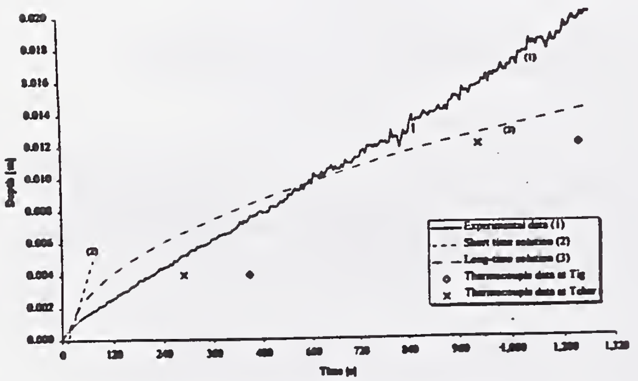


Figure 5c. Char depth, Douglas fir

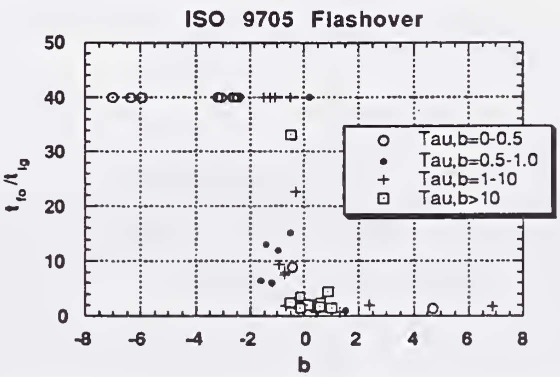


Figure 6. Flashover in ISO 9705

FIRE GROWTH

A criterion for flashover in the ISO 9705 Room-Corner Test can be derived from flame spread principles, and shown to correlate data for over 40 individual tests on a variety of materials. The results are shown in Figure 6. The parameter,b, can be derived from a flame spread model [7] as

$$b = 0.01\dot{m}''\Delta h_c - 1 - 1/\tau_b,\ \tau_{FO} = \frac{t_{FO}}{t_{ig}} \text{ and } \tau_b = \frac{t_b}{t_{ig}}. \tag{15}$$

The dimensionless burning time, τ_b, is also a small factor. Thus, we have tried to show the degree of prediction capable for a range of fire phenomena from derived property data.

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Fire Safe Materials Project at NIST

Takashi Kashiwagi, Kathryn M.Butler, and Jeffery W. Gilman
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8652

Abstract
The results of two studies, which are parts of Fire Safe Materials Project at the National Institute of Standards and Technology (NIST), are presented. One of them is a study of the effects on gasification rates of the addition of silica particles to thermoplastics as flame retardant additives; the other is the development of a gasification model of thermoplastics including the growth and transport of bubbles through the molten polymer that forms on the heated surface.

1. Introduction

The Fire Safe Materials Project is one of the major products in the Building Fire Research Laboratory (BFRL) at NIST. The objectives of this project are: (1) to develop new environmentally-friendly flame retardant principles and fire performance prediction capabilities for the U.S. plastics industry. Industry must be assured that modifications to their products will manifest the intended fire performance without significant reduction of (or even with improvement of) their physical properties. And (2) to enable new/improved U.S. products for domestic & international markets, including evaluation of their economic impacts.

This project consists of five different parts. They are focused on: new flame retardant principles, condensed phase processes, gas phase modeling, characterization of physical properties, and the economics of fire safe materials. The study of new flame retardant principles aims to develop and demonstrate successful application of new flame retardant principles for reducing flammability of commodity polymers and also to understand the flame retardant mechanism. Since polymer-clay-nanocomposites, as one of new flame retardant approaches, with polyamid 6 (PA6), polypropylene (PP), and polystyrene (PS), were presented in the 14th Joint Panel Meeting of the United States-Japan Natural Resource (UJNR) Panel on Fire Research and Safety, a brief discussion will be made of another new flame retardant approach and the results will be presented in this paper. The objectives of the condensed phase study are (1) to understand condensed phase processes during burning of polymeric materials with and without flame retardant additives, (2) to develop a gasification model including thermal degradation chemistry and heat and degradation products transport processes, and (3) to characterize polymer melt-flow behavior and to be able to predict it quantitatively under well-defined conditions. The results in (1) and (2) will be briefly discussed in this paper and those in (3) will be presented by Dr. Ohlemiller in a separate paper. The objective of the study of gas phase modeling is to improve and extend our gas-phase model for the simulation of burning of commodity polymers with and without flame retardants in the Cone Calorimeter. Since this work was presented in detail at the last UJNR Meeting, no discussion of this subject will be given. The objective of the study to characterize polymer physical properties is to

evaluate the elastic, viscoelastic, and fracture properties of the new environmentally-friendly, flame retarded polymeric materials. Finally, the objective of the economic study is to provide an analysis of economic impacts of fire safe materials technology. The last two parts of the project, characterization of physical properties and economics of fire safe materials, are not discussed in this paper due to space limitations.

2. New Flame Retardant Principles

We continue to work with clay-nanocomposites and have formed a consortium to study flammability aspects of clay-nanocomposites for various polymers. Since this approach was presented at the last UJNR Meeting, another flame retardant approach using silica was investigated and is described in this paper. At first, the influence of silica material properties (morphology, surface area, silanol concentration, and surface treatment) on flame retardant effectiveness was determined by preparing silica/PP samples using silicas with very different characteristics. We used fused silica, fumed silica, and a high pore volume (2.0 cm^3/g) silica gel. These samples were prepared by hand mixing powdered PP with the various silicas, followed by compression molding. Table 1 shows the material properties of the four types of silica used. These silicas are very different, specifically in terms of their particle morphology, surface area, and level of silanol functionality. Figure 1 shows representations of the silica types.

Observation of the gasification of the unmodified PP sample in a nitrogen atmosphere first reveals melting of the sample surface at about 30 s after irradiation (incident radiant heat flux: 40 ±2 kW/m^2), followed by the appearance of several large isolated bubbles at the surface, at about 60 s. Continued melting of the sample with more large bubbles was observed at about 90 s. Vigorous bubbling started at about 120 s and the sample surface was covered by a foamy-froth of very small bubbles (very similar in appearance to that of a beer "head") at about 180 s. This can be seen in the top left image in Figure 2. Vigorous bubbling, and a foamy-froth, continued over the rest of the gasification experiment as seen in the middle of the top image in Fig. 2.

The digitized video images of the sample of PP with fused silica (mass fraction 10 %) are not shown in Figure 2; however, similar bubbling phenomena as that of the pure PP sample were observed up to about 200 s. At about 250 s, the surface layer appeared to be more viscous, and had many small bubbles bursting through a more viscous, frothy-foam surface layer. This behavior continued until about 500 s when the surface became solid-like. Scattered white powder was observed after the end of the test, and its weight was close to 10 % of the original sample weight.

The digitized video images of the sample of PP with hydrophobic fumed silica (mass fraction 10 %) are also not shown in Figure 2; however, the behavior was similar to that of the pure PP sample up to about 200 s, with vigorous bubbling but without foaming, or any frothy-foam layer. After about 200 s, the sample had large bubbles rising through a viscous layer. However, this layer still looked like a fluid. After 400 s, some solid-looking islands were observed, and this pattern remained until the end of test. Vigorous bubbling was observed between the islands.

For the sample of PP with silica gel (mass fraction 10 %) initial melting and bubbling phenomena were similar to the above three samples up to about 180 s, as seen in the left bottom picture in Figure 2. At about 180 s, the sample surface rapidly solidified and a crust-like layer formed. It appeared that this layer continued to thicken; the production of the evolved degradation products slowed significantly, as seen in the middle and right bottom images in Figure 2. It appeared that molten polymer below the crust was transported to the surface through the crust by capillary action. The mass of the residue at the end of the test (800 s) appeared to be a rigid crust instead of a powder, and was about 9% of the original sample mass. Although the color of the residue was light gray, it appears that no significant amount of carbonaceous char was formed by the addition of the silica gel. Behavior very similar to the PP/silica gel sample was also observed for the PP/hydrophilic fumed silica sample: except that the surface layer of the residue at the end of the test was very fluffy and white.

The measured mass loss rates of the five samples are shown in Figure 3. The uncertainty in the measured mass loss rate has 5 % relative uncertainty derived from 3 replicate runs of several representative samples. A sharp increase in mass loss rate after about 200 s is clearly seen for the pure PP sample. After 300 s, the mass loss rates of the modified samples decrease in the order: PP/fused silica > PP/ hydrophobic fumed silica > PP/silica gel > PP/hydrophilic fumed silica. However, the mass loss rates of all samples are nearly the same until about 220 s. Actually, the addition of the four silicas slightly increases the mass loss rate before 200 s. This could be due to increased absorptivity of the samples with respect to the incident thermal radiant flux due to the strong broad band absorption of the Si-O peak at about 1100 cm^{-1}, as described later. This tends to absorb the external radiation close to the sample surface, and thus heats the sample surface faster.

From the visual observations of the gasification experiments it appears that the melt viscosity of PP is significantly enhanced by the addition of silica. Both silica gel and hydrophilic fumed silica show the same thickening behavior; with hydrophobic fumed silica and fused silica showing only slight thickening. For the hydrophilic fumed silica the thickening is due to inter-particle hydrogen bonding; on the other hand, the thickening from silica gel can in part be due to this type of mechanism, but entanglement of the polymer in the large silica gel pores may also play a part in increasing the viscosity[1]. After the formation of the crust layer, molten polymer and degradation products may seep through the crust layer toward the surface by capillary action. However, this transport rate through the crust layer tends to be much slower than transport by bubble formation/movement through the much less viscous molten layer in the pure PP sample.

The same types of PP samples were tested in the Cone Calorimeter to examine the effect of each silica type (except for the hydrophilic fumed silica) on heat release rate and mass loss rate during burning. The heat release rate results are shown in Figure 4. The uncertainty in the heat release rate measurement is within ± 10% based on both accuracy of the oxygen analyzer used in the experiments and of heat release rate per unit mass of oxygen consumption used in the data analysis. Although the external heat flux used in the Cone Calorimeter was 35 kW/m^2, instead of 40 kW/m^2 as in the gasification device, the relative order of mass loss rate among the four samples is exactly the same as that shown

in Figure 3. Heat release rate and mass loss rate decrease in the order: pure PP > PP/fused silica > PP/ hydrophobic fumed > PP/silica gel. The above trends indicate that the flame retardant mechanism of silicas tends to be physical in nature, instead of chemical, and also in the condensed phase, instead of the gas phase. Similar results are also obtained with ethylene vinyl acetate, EVA[2].

The basis for the physical effect of silica may be due to the thermal properties of the silica-loaded crust layer. The thermal diffusivities of accumulated silica gel, and of PP, are estimated here. The thermal conductivity [3] of silica varies significantly depending on its porosity. For example, it is 0.015 W/mK for fumed silica, and 1.1 W/mK for fused silica. Here the thermal conductivity of silica gel is assumed to be close to that of fumed silica. The estimated thermal diffusivity of the silica gel is roughly 1×10^{-4} cm^2/s compared to 6×10^{-2} cm^2/s for PP. Although, the value for silica gel is estimated, it is clear that the thermal diffusivity of the silica loaded crust layer should be much less than that of PP. Furthermore, the insulating effect of this layer should improve as the test progresses. The thermal diffusivity of fused silica is about the same as that of PP; therefore we assume that the addition of fused silica to PP does not have any significant effect on the thermal diffusivity of PP.

The reduction in the transport rate of thermal degradation products through the molten polymer layer, due to an increase in melt viscosity by the accumulation of fused silica, could explain the difference in mass loss rate between PP and PP/fused silica, shown in Figure 3. However, since no crust-like layer forms via the accumulation of fused silica, the increase in melt viscosity appears to be much less than that from fumed silica or silica gel. The difference in mass loss rate between PP/hydrophilic fumed silica and PP/hydrophobic fumed silica, shown in Figure 3, is due to the greater increase in viscosity of PP melt by hydrophilic fumed silica as compared to hydrophobic fumed silica, and thus a greater reduction in the transport rate of the degradation products in PP/ hydrophilic fumed silica. Therefore, the silica gel flame retardant mechanism in PP appears to consist of two mechanisms: first, reduction in the transport rate of the thermal degradation products; and second, reduction in thermal diffusivity of the sample near the surface due to gradual accumulation of silica gel, which acts as a thermal insulation layer. This is also true for fumed silica. The reduction in the transport rate of the degradation products is achieved by dramatically increasing the viscosity of PP melts due to hydrogen bonding of hydroxyl groups of silanols, and entanglement of polymer chains with the large pores of silica gel. This transport mechanism tends to dominate early in the test, because a small amount of silanol increases melt viscosity dramatically [1], but the insulation mechanism requires a relatively large accumulation of fumed silica, or silica gel, for the layer to become an effective insulator.

3. Condensed Phase Processes

A condensed phase model is being developed as a part of an overall model to describe the burning behavior of thermoplastics in the Cone Calorimeter. A one-dimensional model has been developed to describe the bubbling behavior of thermoplastic materials exposed to a high heat flux and the effects of these bubbles on thermal and transport properties.

The geometry treated by this model is a horizontal sample of specified initial thickness resting on a non-reactive substrate that satisfies adiabatic thermal conditions at its lower surface. A specified radiant heat flux is applied from above, with losses occurring at the surface of the polymeric sample due to radiation, convection, and reflection. As the temperatures within the sample and substrate rise, the polymer begins to decompose into gaseous components. This model focuses its attention on the finite-rate transport of these gases to the sample surface and on the effects of gases contained within the sample on its thermal behavior and mass loss rate.

The one-dimensional bubble model is based on finite element theory. The sample is divided into a large number of elements in the direction perpendicular to the heated surface, with elements bounded by nodes. Initially, the thicknesses of all elements are identical, and a bubble of zero size is located at the midpoint of each element. The external heat flux is applied, and the nodal temperatures at the next time step are determined by standard finite element techniques. During each timestep, gasification takes place within each element. The amount of gas generated during the timestep is determined by integrating an Arrhenius expression over the element thickness. The gas is then apportioned to one or more bubbles located within the element.

At this point in the calculation, each bubble is represented by a one-dimensional gas layer, whose increase in thickness is linked to a decrease in polymer layer thickness by mass conservation and the ratio of gas density to polymer density. To determine the movement of this gas, the thickness of the bubble and its growth rate are converted to an equivalent radius and radial growth rate. Stokes flow calculations of bubble velocity due to viscosity gradients, surface tension gradients, and buoyancy now relocate each bubble within the sample. If a bubble touches the upper surface, it is considered to have "burst." The sum of the masses of gas from all bubbles that have burst during this timestep determines the current mass loss rate. These bubbles are removed from further calculations. If any element is left without a bubble after the bubbles are moved, a new bubble of zero size is located at its midpoint.

The volume fractions of gas and polymer can now be computed in each element from comparison of the thicknesses of gas layers (bubbles) whose centers are located within the element to the thickness of the remaining polymer. The total element thicknesses and the locations of nodes are also adjusted. The volume fractions combine with material properties of the gas and polymer to determine the equivalent thermal conductivity, density, and specific heat of each element, and element velocities are calculated from the motion of polymer and gas during this timestep.

The attached figures show the mass loss rate, Figure 5, and a time sequence of the bubbling sample, Figure 6, that result from this numerical procedure for a sample of polypropylene. The cross-sectional area of the computational space is determined by the bubble number density, and bubbles are assigned a random location in the horizontal direction for visualization purposes during this time step. The next finite element calculation of temperature is now performed. This procedure continues until the polymer has completely gasified.

References
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[3]" CAB-OSIL Untreated Fumed Silica Properties and Functions" Cabot Corp. TD-100, May(1997).
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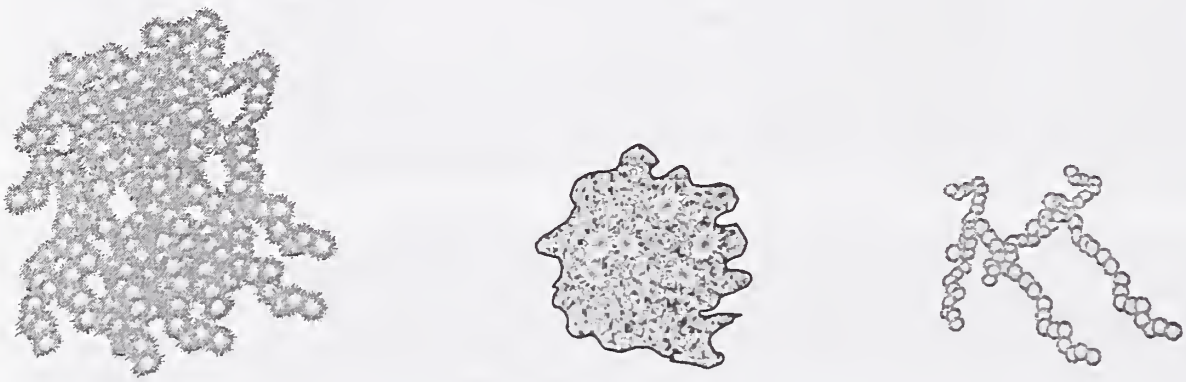

Figure 1. Drawing representing the different silica-morphologies for silica gel (left), fused silica (center), and fumed silica (right).

Tablel 1. Material properties of various silicas.

Silica	Porosity (cm^3/g)	Thermal Treatment (°C, h)	Silanol Density ($SiOH/nm^2$)	Surface Area (m^2/g)	Particle size (μm)
Fused Silica amorphous	~ 0	100 °C 2h	low	low	7
Fumed Silica hydrophilic	NA	None	3 - 4	255 ± 25	aggregate length 0.2 – 0.3
Fumed Silica hydophobic[a]	NA	100 °C 15h	1 - 2	140 ± 30	" "
Silica Gel	2.0	900 °C 15h	0.4	400 ± 40	17

a: ~ half of the SiOH groups are capped by trimethysilylation [4].

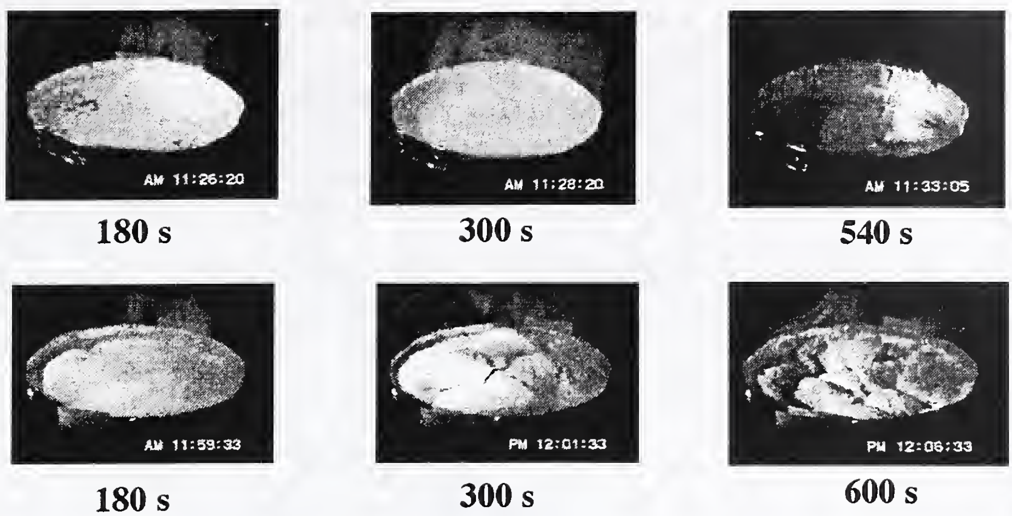

Figure 2. Digitized images of sample surface during gasification in N_2 at 40 kW/m^2. Pure PP (top row); PP with silica gel (mass fraction 10%) (bottom row).

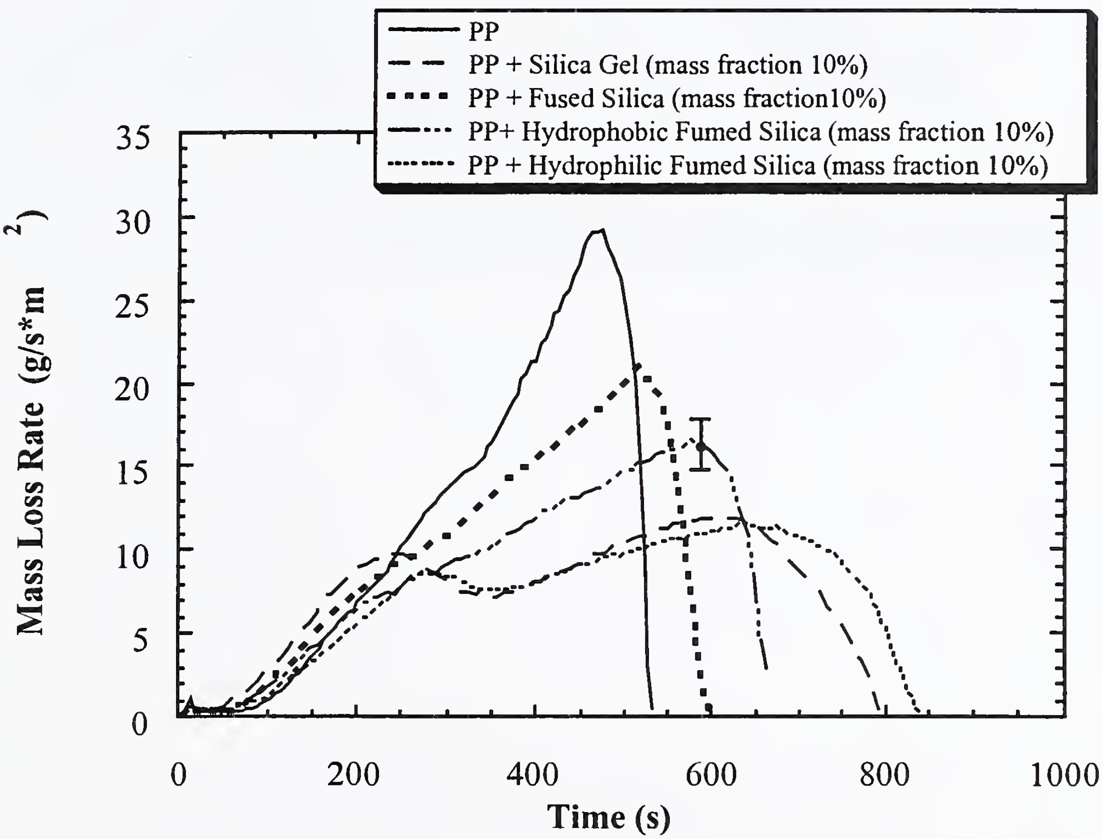

Figure 3. The mass loss rate data from the gasification (N_2 at 40 kW/m^2) of: pure PP, PP/silica gel, PP/fused silica, PP/hydrophobic fumed silica, and PP/hydrophilic fumed silica. This shows the effect of silica type on the gasification rate of PP.

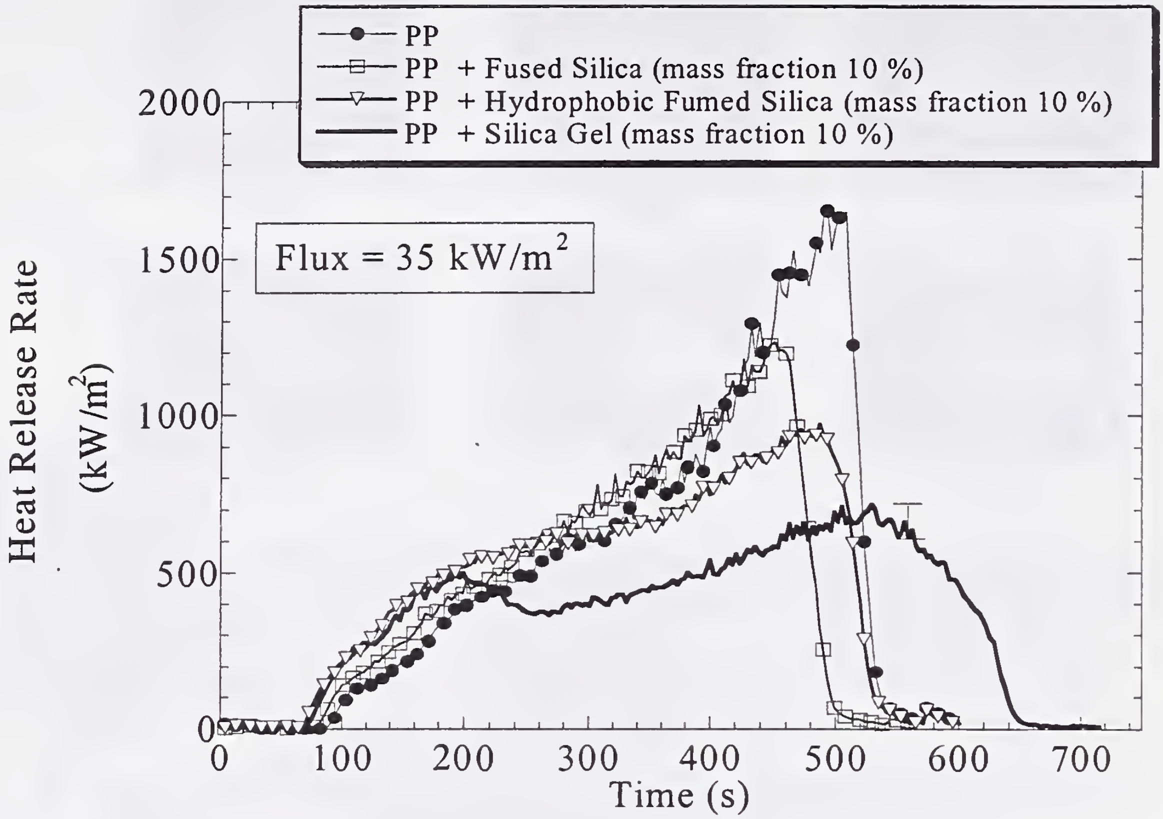

Figure 4. Effects of the addition of various silicas on heat release rate of PP

Reference

[1] R.K. Iler, The Chemistry of Silica, John Wiley & Sons, New York, p. 588 (1979).

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Influence of Polymer Melt Behavior on Flammability

T. J. Ohlemiller and K. Butler
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

Abstract

As the initial step in a study of the role of polymer melt viscosity in polymer burning behavior, a simpler, non-burning configuration has been examined. Vertical slabs of two types of polypropylene have been subjected to uniform radiative heating on one face. The subsequent melt flow process was monitored by measuring weights, temperatures and flow velocities. A low MW polypropylene flowed freely at temperatures below those for significant degradation whereas a commercial polypropylene of higher MW degraded and gasified extensively. Plans are described for modeling the non-reactive case first.

Introduction. In certain consumer product areas, such as electronic devices and automobiles, complex molded parts made from thermoplastic polymers are increasingly common. Low part costs for large production runs and the ability to integrate into one piece what formerly required several individual parts make this a trend which is likely to continue. The commodity polymers, such as polypropylene and polystyrene, which are used for these components are inherently flammable unless properly treated with flame retardants. However, as noted by Kashiwagi [1] in another paper presented here, there is a shift occurring in the nature of acceptable flame retardants for ecological reasons. These two trends, the growth in thermoplastic components and the shift in the nature of flame retardants, provide an incentive to look at the flammability behavior of thermoplastics and to assess the extent to which this behavior may affect the appropriate choice of new means of flame retardancy. This paper is a progress report on a study of these issues.

Experience with the burning of thermoplastic automotive components has demonstrated that it is a very complex process dependent on several factors. The central complexity, long recognized, is that thermoplastics inevitably change shape as they are subjected to the heat of the burning process. This is probably the chief reason why the literature contains few results in this area [2, 3]. Time-dependent changes in fuel geometry make modeling of the burning process much more challenging.

Shape change is typically accompanied by the movement of hot, lowered viscosity material to some new location under the influence of gravity. This polymer "melt" may be burning, both as it moves and in its new location. Thus the growing fire on the part re-shapes it, moving heated material and this, in turn, alters the fire growth process. The net result can depend strongly on where the moving material comes to rest and on the thermal properties of the material on which it

rests. Thus, for example, the polymer melt can form a burning pool near the original part location so that the flames from this pool interact with this burning part or, in the opposite extreme, the melt can fall a substantial distance and be quenched on a cold, heat absorbing surface, thus robbing the original fire of fuel. The heat release rate of such a thermoplastic part can thus vary strongly with the physical circumstances in which it is burned.

The above behavior is not seen when testing horizontal samples of material in the Cone Calorimeter. When one is assessing new flame retardant materials for thermoplastics, it is desirable to also look at them in modes that resemble their likely real world behavior.

As a first step along the above lines, NIST has initiated a study of polymer melt behavior in a very simple configuration: a thick, vertically oriented slab. Before examining the burning process itself, we are looking at an idealized version of it to see if this can be modeled. Thus this slab of thermoplastic is subjected to spatially uniform radiative heating on one surface.

Description of Experiments. Figure 1 is a sketch of the polymer heating experimental apparatus. A panel heated by the burning of natural gas uniformly irradiated the front face of a polymer sample (5.7 cm wide by 25 cm high by 25 mm thick). The sample was insulated on its lateral edges and its back surface; its weight was measured by a scale which supported the sample frame. This scale had a resolution of 1 g. Polymer melt material was captured by a pan atop a second scale after a free drop of about 30 cm. This scale had a resolution of 0.1 g. The temperature of both scales was monitored to assure that they did not heat significantly.

In separate experiments the radiant flux to the polymer samples was varied. The intent was to hold this flux constant during the exposure (which began with the removal of a water-cooled shutter). However, the panel showed an initial spike in its flux of 25 % or more above the test-average flux (apparently because of variation in the rate of radiative losses from the panel in the presence vs absence of the shutter). The transient behavior of the flux was followed by a flux gage placed next to the sample; the initial spike decayed after about 2 min to 3 min. The time-average radiant flux (which is the value reported below) was varied from the lowest level at which the panel remained reasonably stable (ca. 8 kW/m^2) to flux levels somewhat less than those seen in wall flames (maximum here of 26 kW/m^2). The flux gage was calibrated against a standard and should have an uncertainty within ± 5 %. The exposure time was varied from 10 min at the highest fluxes to 45 min at the lowest.

At intervals during a test, a mechanically-supported thermocouple (0.05 cm dia. sheath; chromel/alumel) was inserted nearly tangentially into the outer portion of the surface melt layer to get a measure of this surface temperature. This was done at two heights on the vertical centerline of the sample, usually about 5 cm from the top and 5 cm from the bottom. There were small systematic differences between the measurements at the two heights which have not yet been analyzed; the average is reported here. The temperature readings from this thermocouple varied with its exact placement (affecting the extent of lead wire wetting by the melt); the values reported are the maxima. There is insufficient information to assess the absolute accuracy of this result as a measure of melt surface temperature. A single thermocouple was placed at the back of

the sample (near its center) at its interface with the 25 mm block of ceramic fiber insulation there. A single thermocouple (bare junction made from 0.013 cm dia. chromel/alumel wire) was also placed in the melt pool, just above the catch surface, near the point at which melt material flowed in.

Small flakes of thin Kapton[1] polyamide (0.013 mm thick; typically ca. 3 mm square) were placed onto the upper region of the melt surface at intervals to serve as a means for estimating the downward flow velocity of the outer surface of the melt. The behavior of these was recorded by a Hi-8 video camera. The data have not yet been analyzed but preliminary tests gave velocities on the order of 1 cm/s.

Preliminary tests were performed with commercial grades of low density polyethylene, high density polyethylene and polypropylene. The two polyethylenes exhibited a skin-forming behavior during heat-up which rendered their subsequent melt flow erratic and very complex. Thus the work reported here has focused on polypropylene which shows only some yellowing during heat-up. The results below compare the behavior of a commercial polypropylene (here denoted as PP) and a low molecular weight polypropylene having a weight mean molecular weight of 23,000 (here denoted as 23kPP).

The melt viscosity of the polymer as a function of temperature is a key determinant of its behavior in these experiments (and during burning). A rheometer was used to obtain preliminary measures of viscosity as a function of temperature and shear rate.

Experimental Results and Discussion. Figure 2 shows the approximate steady-state mass loss rate from the two types of polypropylene as a function of the incident radiant heat flux. (The mass loss behavior was nearly steady for these tests but the values shown are those from late in each test where the loss rate was a maximum.) The commercial material was barely hot enough to begin to lose mass in a 45 min exposure at 8 kW/m^2; as the incident flux was increased, the mass loss rate became substantial. The 23kPP, on the other hand flowed freely, even at the lowest heat flux; this loss rate increased almost linearly with an increase in the flux. Curves for both materials imply that the loss rate would be still greater if the heat flux were increased to the level (30 kW/m^2 to 40 kW/m^2) provided by flames on a vertical surface at this scale.

Rheometric measurements on these materials are in need of further study but they show a substantial shear rate dependence, indicative of non-Newtonian behavior. The zero shear viscosity of the commercial PP is, of course, much higher than that of the 23kPP. The difference is so large that measurements could not be made in overlapping temperature ranges. Thus the 23kPP shows an apparent viscosity which decays to small values (few Pa-s) by ca. 175 °C; the

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[1] Certain trade names and company products are mentioned in the text in order to specify adequately the equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

commercial PP reaches comparable viscosity values only well above 250 °C (measurements have yet to be made above this temperature). All measurements thus far have been in air; nitrogen may give different behavior due to lack of oxidative interactions which can alter the molecular weight and thus the melt viscosity. It is not feasible to measure viscosity at high temperatures, comparable to those reported below for the surface temperature of the commercial PP.

Figure 3 shows the average surface temperatures for the two materials in the same incident heat flux range. Note that at equal heat fluxes the surface temperature of the 23kPP was as much as 200 °C less than that of the commercial PP. At the same time its mass loss rate was roughly twice as high. This was simply a result of the low melt viscosity of the 23kPP. Nearly all of the net absorbed heat was being carried away as the sensible heat content of the polymer melt. Figure 4 shows that virtually all of the mass lost from the 23kPP ended up in the melt pool. Note that there is no indication that fire level heat fluxes would change this. Note also that the data for this material imply that it would be difficult to make it burn in this vertical configuration because it tends to "melt" away at a temperature too low to provide any gas phase fuel.

Figure 4 also shows that slightly less than half of the commercial polypropylene ended up in the melt pool. The remainder had been vaporized. Rather surprisingly, the fraction vaporized did not change appreciably as a function of heat flux even though Figure 3 shows that the surface temperature was varying by about 150 °C over the flux range examined here (recall also the exposure time varies from 10 min to 45 min, inversely with the heat flux). Some further tests are planned to check the apparent constancy of the fraction vaporized in light of the small mass losses at the low flux end. Figure 4 implies that during burning about half of the commercial PP would feed a flame on the face of the sample and half would flow away to burn in a melt pool. Burning experiments are planned to check these inferences.

From a modeling standpoint, the 23kPP appears simpler. The data here suggest that this experiment could be modeled without the inclusion of any degradation chemistry. The commercial PP, on the other hand, degraded extensively in these tests. Viscosity measurements on material from its melt pool gave values much lower than on the starting material, implying a substantial decrease in molecular weight. This could be the result of both pyrolytic and oxidative reactions in the present set-up where air had free access to the hot surface.

Model Description. Polymer melt behavior is very complex; even the simple two-dimensional configuration studied here poses a challenge to the modeler. The most basic description must include equations of mass, momentum, and energy, with flow driven by gravity and temperature rise dictated by an imposed heat flux. The geometry of the problem changes considerably with time. The surface of the melt is a free surface that may undergo considerable deformation, and the internal interface between the solid and melted polymer moves through the material as it heats. The flow is in large part determined by wide variations in viscosity, whose strong dependence on both temperature and molecular weight should ultimately be included in the model. If the temperature increase is high enough, the polymer begins to gasify, and chemical reactions must be taken into account in calculations of heat and mass transport. The material properties of the vertical holder also affect the heat transport.

This complex problem can be modeled using the capability of the commercial finite-element program FIDAP. This software provides the means to model flow processes involving arbitrary changes in shape, including breakup and merging of fluid volumes. Free surfaces are described using a volume of fluid (VOF) method, in which a marker concentration field variable is set to unity within the fluid of interest and to zero outside. The free surface itself is located by steep gradients in this variable. The solution proceeds by alternate applications of Galerkin finite energy techniques to solve for mass, momentum, and energy and the VOF method to determine the new locations of free surfaces. The local mobility of the fluid depends on its viscosity, which may be entered as a function of temperature and other variables. The polymer behaves as a solid where the viscosity is very high, and the melt front within the polymer can be located by the deepest nonzero velocities. Additional flexibility is provided in FIDAP by adaptable species equations and user-defined subroutines.

Figure 5 shows the two-dimensional input geometry for modeling the polymer melt experiment. In addition to the melting behavior of the vertically mounted polymer, the free surface capabilities of this software enable the model to consider the behavior of the melt after it has fallen away from the holder. No-slip boundary conditions are applied to the wall behind the polymer, the solid lip that holds the polymer in place, and the catch basin. The side wall is insulated, and a radiative heat flux is applied to the melt surface. Either the temperature of the catch basin or the heat flux through it is fixed. The polymer sample initially occupies a rectangular space and is assigned the appropriate material properties for polypropylene.

Both the chemical reaction responsible for polymer gasification and non-Newtonian viscosity behavior are easily included in this model. This model can also be used to investigate conditions under which the molten polymer that has dripped from the sample continues to degrade and contribute to the available fuel. The eventual extension of this model to burning polymers will be considered.

References

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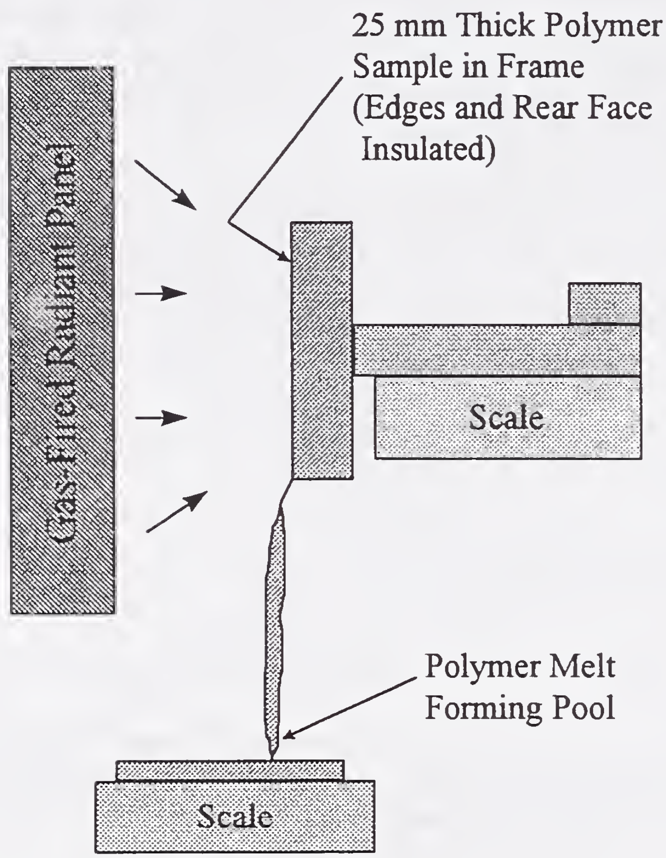
3) Kashiwagi, T., Omori, A. and Brown, J., "Effects of Material Characteristics on Flame Spreading," Fire Safety Science - Proceedings of the Second International Symposium, International Association of Fire Safety Sciences, Hemisphere Publishing, New York (1989) p. 107

Figure 1. Polymer Melt Apparatus



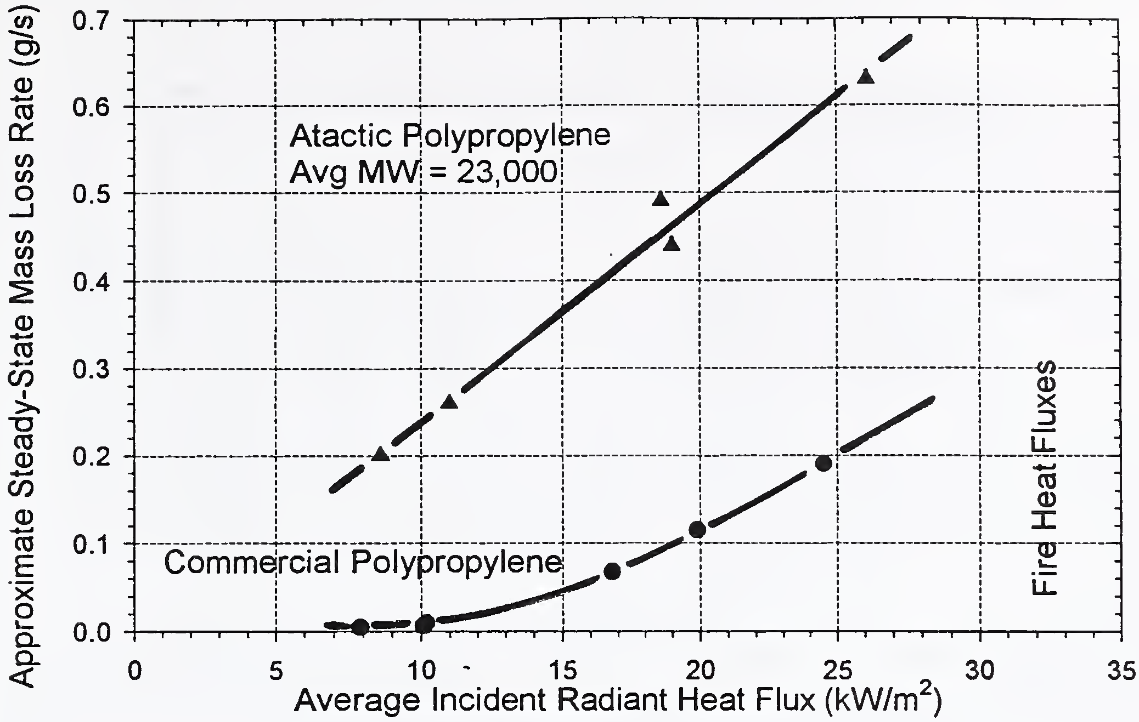


Figure 2. Steady-state mass loss rate from two types of polypropylene as a function of incident radiant heat flux.

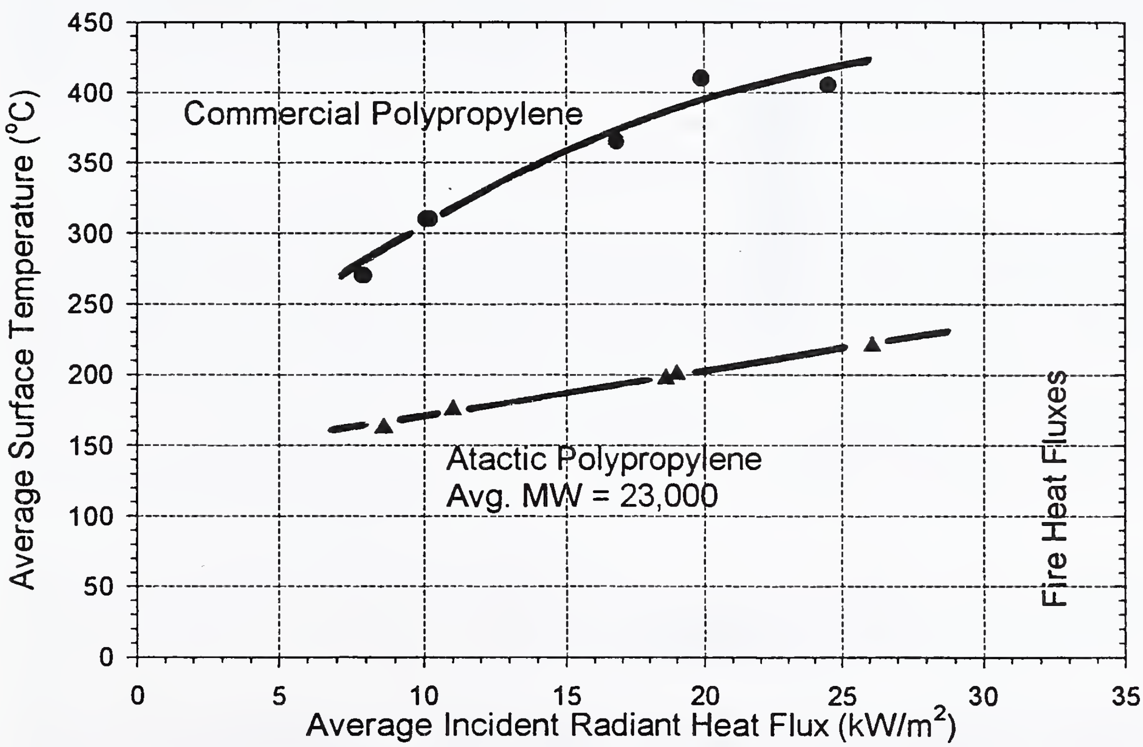


Figure 3. Average surface temperature for two types of polypropylene as a function of incident radiant heat flux.

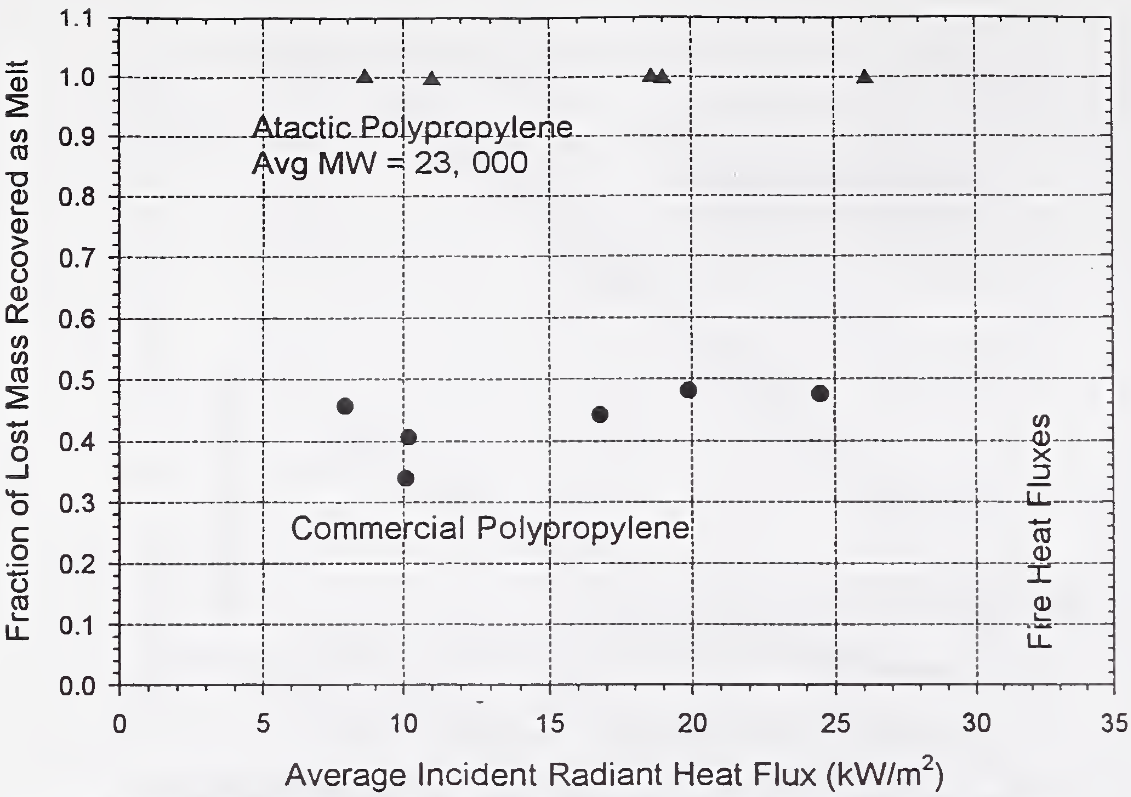


Figure 4. Fraction of mass lost from sample that is recovered in the melt pool for two types of polypropylene, as a function of incident radiant heat flux.

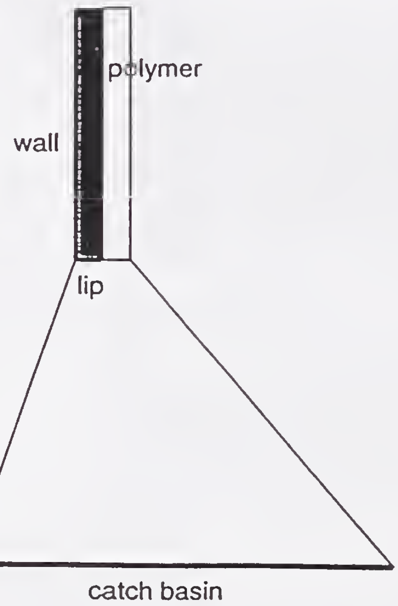


Figure 5. Computational domain for modeling the melt behavior of a polymer heated on one exposed, vertical surface.

FLAMMABILITY TEST FOR FLAME RETARDANT PLASTIC PALLET

Tokiyoshi YAMADA
Eiji YANAI and Hidefumi NABA,
National Research Institute of Fire and Disaster
14-1, Nakahara 3-chome, Mitaka,
Tokyo, 181-8633 JAPAN

Masahiro SAGARA,
Mitsugu HAGA and Hiroji FUKUMOTO
Japan Pallet Association
14-12, Ginza 2-chome, Chuo-ku,
Tokyo, 104-0061 JAPAN

Tsuyoshi KOBAYASHI
Rinkagaku Kogyo CO.,Ltd.
34 Shin-bori, Shin-Minato, Toyama Pref.,
935-0034 JAPAN

ABSTRACT

Fire risk of plastic pallet was recognized by a big rack storage fire occurred in Japan on Nov.1995. Thereafter NRIFD started research and development of fire-retardant (FR) plastic pallets in collaboration with Japan Pallet Association and a fire retardant chemical company. Flammability and mechanical properties of some FR synthetic resins are examined to select appropriate synthetic resins for plastic pallets. The flammability of the resins is tested by the cone calorimeter, UL94 and the Oxygen Index Test prescribed in Japan Industrial Standards (JIS) K7201, and comparisons are made between each of test results. Finally the prototype of FR plastic pallet is produced of the FR plastic combined by $Mg(OH)_2$ and red-Phosphorus. The fire tests of full-scale pallets are conducted with furniture calorimeter and the effect of the fire retardant is examined.

INTRODUCTION

A fire occurred in a warehouse in Japan on Nov.1995. This warehouse had automatic high-palletized rack system and many plastic pallets were stored for stacking noncombustible products. Automatic sprinklers were installed and activated, however the fire spread very rapidly and fire suppression failed. The fire continued for more than 18 hours and three fire fighters were killed. After investigation of the warehouse fire [1], Fire and Disaster Management Agency addressed some fundamental countermeasures, i.e., 1) enhancement of fire safety equipments such as sprinkler installation, 2) mitigation of fire risk caused by plastic pallets including adoption of inflammable or fire retardant (FR) treated plastics.

In July 1998, the Fire Service Law Enforcement was revised to enhance fire safety countermeasures in warehouses and a new guideline [2] of the sprinkler installation is proposed depending on the total amount of heat source in warehouses. In this guideline, a new class of combustible material is introduced as "high calorie melting material", in which the threshold of heat release is set to be 34 MJ/kg. In addition to the conventional "designated combustibles" prescribed by Fire Service Law Enforcement, the total amount of such material including plastic pallets should be taken into account for installation of sprinklers.

As far as the FR plastic pallets are concerned, there are many research and development of FR plastic material [3][4][5], however very few FR pallets have been developed in Japan. The major material of the

plastic pallets prevailed in the market is olefin hydrocarbons such as polypropylene (PP). And as the FR chemicals for such plastic, halogen containing (mainly bromine compound) and non-halogen containing (magnesium hydroxide ($Mg(OH)_2$) with diantimony trioxide (Sb_2O_3)) are commonly used. As for the flammability classification of these FR plastics, UL94 [6] and the Oxygen Index test in JIS K7201 [7] are very popular in Japan. Especially special attention is paid for the Oxygen Index, because Fire Service Law Enforcement designated the plastic material of less than 26 in oxygen index as "flammable". A plastic pallet test has been proposed by UL2335 [8], however this is not well known in Japan currently.

Under these circumstances, development of FR pallets is one of our key issues for improving warehouse fire safety, and rational test methods to evaluate the flammability of plastic pallets are needed. National Research Institute of Fire and Disaster conducted research and development in collaboration with the Japan Pallet Association and a fire retardant chemicals company. The following describes the development process in three stages and related flammability test results by using cone and furniture calorimeter, UL94 and the Oxygen Index tests.

BLOCK FLOW OF THE R&D PROJECT

One of our immediate goals is to develop and introduce less flammable prototype plastic pallets which can be used practically in the near future. In this collaboration of R&D project, FR plastic pallets made of polypropylene basis were developed in three stages as shown in Figure 1. In each stage, flammability and mechanical properties are examined.

1st stage : Screening test for selecting flame retardant additives (bench scale)

[target test resin] (two kinds of halogen containing and five nonhalogen retardant chemicals)

↓

2nd stage : Screening test for finding the ratio of combination of flame retardant additives (bench scale)

[target test resin] (total eight fire retardant treated with non-halogen magnesium hydroxide)

↓

3rd stage : Plastic pallets burning Test (1/4 piece of full scale)

[target test plastic pallets] (four combinations of two kinds of red-phosphorus by two kinds of magnesium hydroxide)

Figure 1. Outline of development process

RESULTS & CONSIDERATIONS

The 1st stage development

At the beginning of this R&D project, popular FR chemicals for basic resin PP are examined in bench scale by the cone calorimeter, UL94 and the Oxygen Index Test.

Test resins and flammable test : FR chemicals are classified roughly into two types, i.e., halogen and non-halogen containing additives. Recently adoption of the halogen additives tends to be avoided due to envi-

Table 1. Properties of test resins for plastic pallets
(the 1st stage screening test for selecting valid flame retardant chemicals)

Test Plastics			Properties				
	No.	fire retardant chemicals*1) [weight %]	Color observation —	Density JIS-K7112 (kg/m3)	Burning Test UL94*2) rating	Heat of Combustion calorimeter*3 (kJ/g)	Oxgen Index JIS K7201 —
refference	J−750HP	base Poly-ropyren	Natural	0.90	HB	46.6	17.9
Red-Phosphorous flame retardant	EX696	r-P[8.3]+polyphosphate-melamine[	Brown	0.99	V-2 out	41.7	22.7
	EX697	r-P[4.3]+Mg(OH)2[8.7]	Brown	1.14	V-2 out	31.0	22.2
	EX698	r-P.(4.5)+melamine-cyanulate[5.4]	Brown	0.95	V-2	43.7	19.6
	EX699	r-P[9.1]	Brown	0.95	V-2	44.5	20.3
Halogen and Non-halogen flan retardant	EX168S	$Mg(OH)_2$[10]	Gray	1.37	V-2	20.6	24.3
	EX187	Br + Sb_2O_3[20]	Gray	1.01	V-1	40.7	26.4
	8200R	Br+Sb_2O_3*[not disclosed]*	Gray	0.99	V-0	41.1	30.3

*cf . *1) r-P is red-phosphorous flame retardant additive*
**2) The rating on this table is corresponding to the UL 94 test rating, however those are not certificated by the UL..*
**3) Oxgen Bomb calorimeter.*

ronmental issues. In this development, two specimens of popular bromine halogen (non DBDPO type) FR treated resins are examined as reference. As non-halogen FR additives, popular $Mg(OH)_2$ is selected and r-P is also added to the resin. Table 1 shows the test resins examined in the 1st stage including base resin PP as reference.

Cone calorimeter test : Figure 2 shows the time curve of heat release rate of different FR treated resins and non-FR base resin PP. "8200R" and "EX187" containing bromine additive show similar time curve. These FR additives have an effect on suppressing ignition and burning rate. However, once the specimen burns, the FR effect becomes smaller and the heat release rate decreased only 20% less than that of the base PP. Regarding the plastic "EX-168S" to which $Mg(OH)_2$ is added, the total amount of heat release is 44% of the base PP. So the heat release rate becomes relatively lower and the peak heat release rate becomes about 20% compared with that of the base PP. And moreover dehydrated residue of the $Mg(OH)_2$ remains in layers on the surface and it gives thermal insulation effect which causes less burning rate.

In the case of only r-P is added, the peak heat release rate(PHR) is reduced by only 20% or 30%. However, being combined with melamine containing FR chemicals increases the FR effect. The test result shows that especially when r-P chemicals combined with polyphosphate melamine, the PHR is half the PHR of base PP. The above qualitative combustion phenomena can be observed under other radiant heat flux condition. The effect of the radiant heat flux will be mentioned later.

FR treatment on resins reduces heat release rate and retards ignition time, however generally it enhances to generate the large amount of hazardous combustion products. Figure 3 shows the time curve of CO yield. The figure indicates the CO yield generated from halogen-containing FR resin ranges from twice to three times in the peak compared with that of base PP. In contrast, in the case of $Mg(OH)_2$ additives, the smoke production is very small and the CO is hardly measured. When r-P is added, the amount of smoke is getting higher than that from the basic PP.

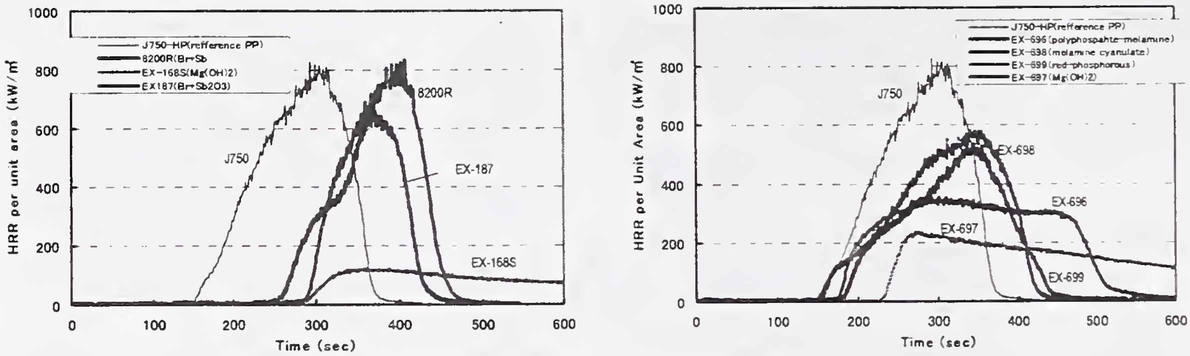


Figure 2. Heat release rate of FR treated plastics
(mixture of r-P and $Mg(OH)_2$; under 20 kW/m^2 radiative heat flux)

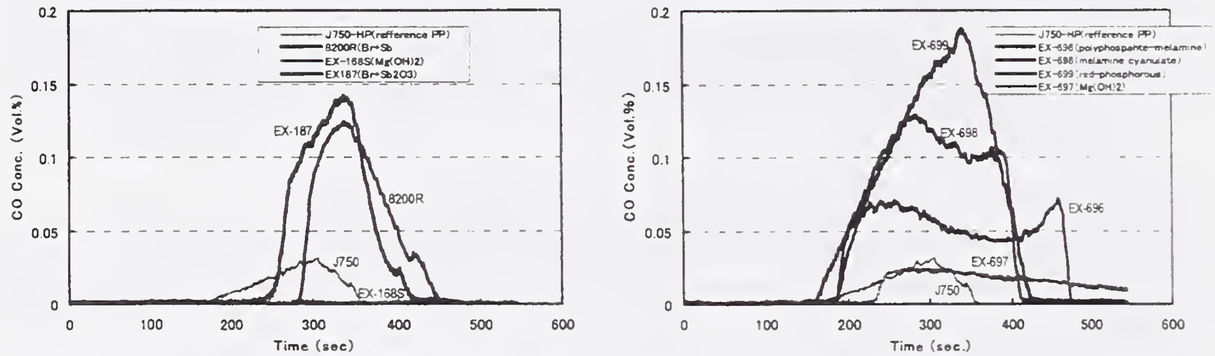


Figure 3. CO yield of FR treated plastics
(mixture of r-P and $Mg(OH)_2$; under 20 kW/m^2 radiant heat flux)

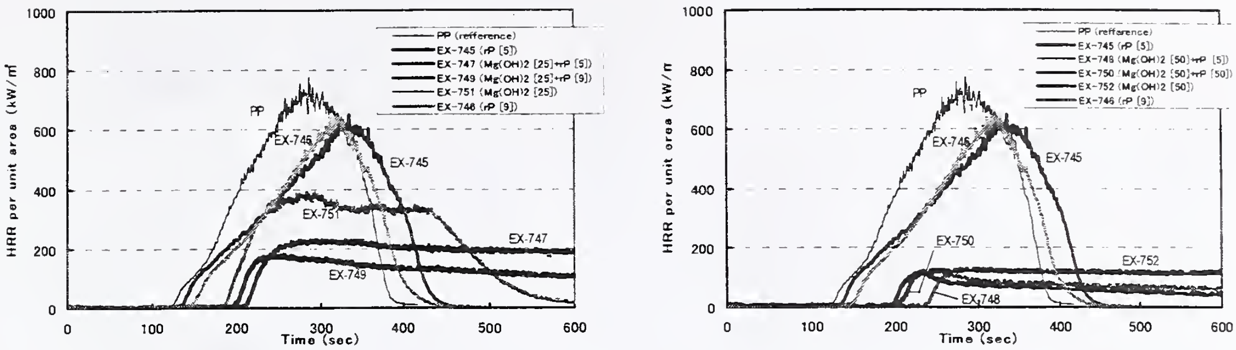
The 2nd stage development

Test resin and flammable test : From the flammability screening test results in the 1st stage, it is observed that FR additive of $Mg(OH)_2$ has relatively high FR effect. Then further details of weight ration of $Mg(OH)_2$ and the combination of $Mg(OH)_2$ and r-P are examined in the 2nd stage. As the basic FR

Table 2 Properties of test plastics for pallets : (the 2nd stage screening test for finding appropriate combination of flame retardant chemicals, i.e. r-P and $Mg(OH)_2$)

Test Plastics			Properties				
	No.	fire retardant chemicals*1) [weight %]	Color observation —	Density JIS-K7112 (kg/m3)	Burning Test UL94*2) rating	Heat of Combustion calorimeter*3) (kJ/g)	Oxgen Index JIS K7201 —
refference	PP	base Polypropyren	Natural	0.89	V-2 out	46.6	17.7
Red-Phosphorous added FR	EX745	r-P[4.8]	Brown	0.92	V-2 out	45.5	19.5
	EX746	r-P[9.1] (=EX699)	Brown	0.95	V-2	44.5	20.2
	EX747	r-P.[4.6]+Mg(OH)2 [25]	Brown	1.09	V-2 out	33.7	22.3
	EX748	r-P.[4.6]+Mg(OH)2 [50]	Brown	1.31	V-0	22.9	26.5
	EX749	r-P.[9.1]+Mg(OH)2 [25]	Brown	1.22	V-2 out	33.1	23.4
	EX750	r-P.[9.1]+Mg(OH)2 [50]	Brown	1.35	V-0	22.0	28.8
$Mg(OH)_2$ base FR	EX751	$Mg(OH)_2$[25]	Gray	1.05	V-2 out	35.0	19.8
	EX752	$Mg(OH)_2$[50]	Gray	1.28	V-2 out	23.7	22.9

*(cf) *1) r-P is red-phosphorous flame retardant additives*
**2) Ratings on this table correspond to the UL 94 test rating, however those are not certificated by the UL..*
**3) Oxgen bomb calorimeter.*
**4) The value derives from the property of popular pallete made of PP.*



(a) FR additives of 25 wt% of $Mg(OH)_2$ and /or r-P. (b) FR additives of 50 wt% of $Mg(OH)_2$ and /or r-P.

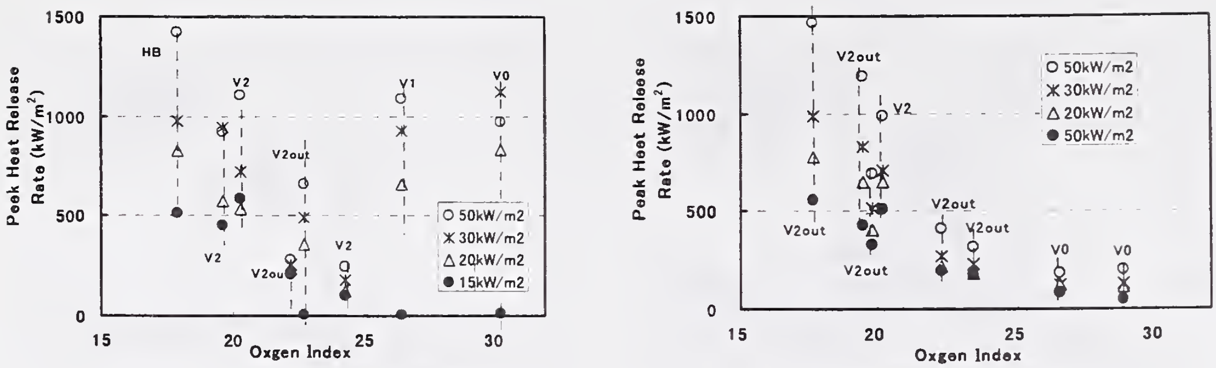
Figure 4. Heat release rate of FR treated plastics in the 2nd stage (mixture of rP and $Mg(OH)_2$; 20 kW/m^2 radiative heat flux)

chemicals, $Mg(OH)_2$ 50wt% and 25wt% are prepared and r-P is added with 4.6wt%,9.1wt% and none respectively. Table 2 shows the test resins examined and some of the test results.

Cone calorimeter test : Figure 4 shows the heat release rate in the cases where $Mg(OH)_2$ is of 25wt% in the left side (a) and 50 wt% in the right side (b) with test result of base PP as reference. The figures indicate that adding only r-P suppresses heat release rate after ignition, however the PHR is reduced only by 20%. When only $Mg(OH)_2$ is added, the PHR rate is highly reduced and slower combustion continues. When $Mg(OH)_2$ is of 25wt%, the FR effect of red phosphorous additives is larger than that in the case of 50wt% of $Mg(OH)_2$. In the case of $Mg(OH)_2$ FR treatment, combustion product is suppressed because heat release rate is small as observed in the 1st stage.

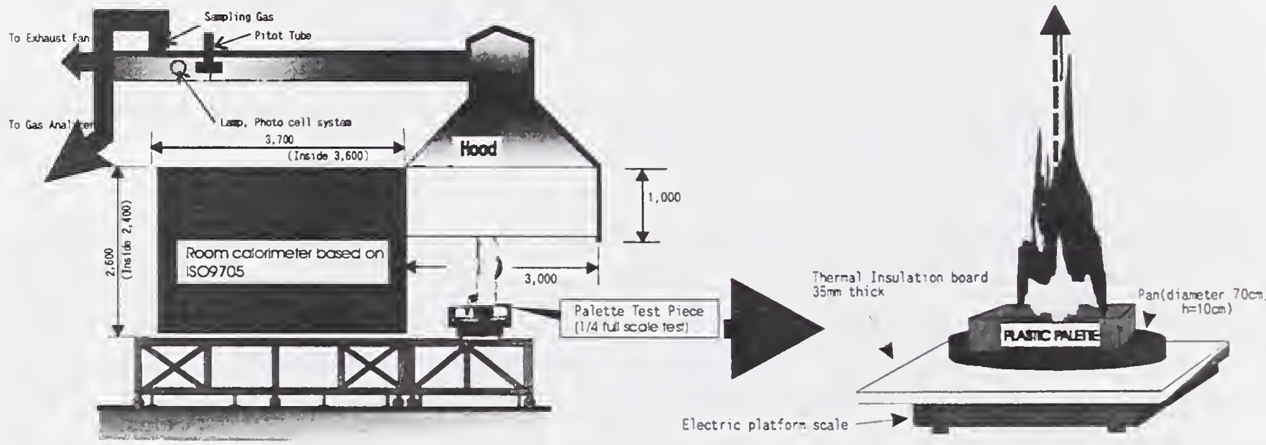
Relation between PHR by cone calorimeter & other flammability test classification

The PHR obtained by the cone calorimeter seems to be one of the important indices for fire safety. Figure 5 shows the relation between the PHR and flammability classifications obtained in other tests (oxygen index and UL94 test) in the 1st and 2nd stage. As shown in this Figure, the PHR decreases as the oxygen index increases. This tendency can be clearly observed in the 2nd stage test for non-halogen FR treated resins (Figure 5 (b)). When oxygen index is more then 26, heat release rate is very low and the UL94 classification corresponds to "V0" consistently. The Oxygen Index 26 is the criterion value to determine "flammable/inflammable synthetic resin" in Japan as mentioned above. However in the 1st stage test, even though the bromine containing FR treated resins give more than 26 oxygen index value and V0 or V1 UL94 classification, the PHR under radiant heat flux becomes higher than that of other FR resins. It indicates that the halogen containing flame retardant material retards ignition time, however once it burns, halogen chemicals burns as additional heat source. The "V2" classification resins tested by the UL94 test are in the range between 19 and 24 of oxygen index, however clear relation between oxygen index and "V2" and "V2 out" classifications are not found.



(a) 1st stage test result (b) 2nd stage test result

Figure 5. Relation between PHR by cone calorimeter & other flammability test classification



(a) Installation (b) Detail of 1/4 piece of plastic pallet burning test

Figure 6. Experimental Setting for 1/4 piece of plastic pallet burning test

The 3rd stage development

Test resin and flammable test : In the 2nd stage, three flame retardant plastics, Ex-752 ($Mg(OH)_2$(50wt%), EX-748 ($Mg(OH)_2$[50wt%]+r-P[4.6%]) and EX-750 ($Mg(OH)_2$ [50wt%]+r-P[9.1wt%]) are finally selected from the view point of both mechanical and combustion properties for plastic pallets. The two of them added with r-P correspond to "V0" classification by the UL94 test. Plastic pallets in full scale size are produced of the material and the combustion tests are conducted with furniture colorimeter as shown in Figure 6 and Table.3.

The size of the plastic pallet is about 1,110 x 1,110 x h.150 mm. 1/4 piece of the pallet is used for the burning test. The test piece is located on the stainless steel pan of 70cm diameter and 10cm depth as shown in Figure 6. Three sizes of methanol pan are adopted as ignition heat source, i.e., 5cm diameter pan with 20 cm^3, 10cm with 40cm^3 and 20cm with 80 cm^3 methanol. The ignition heat source is located at the center of the 70 cm diameter pan. In addition, solid fuel of 3cm diameter x h.1cm tablet made of Hexamethylenetetramine is used and put on the top surface of the plastic pallet. This supposes the case when burning firebrands of dripped plastic cause fire to spread downward.

Table 3. Burning test list of 1/4 piece of full scale pallet by furniture caloriemeter

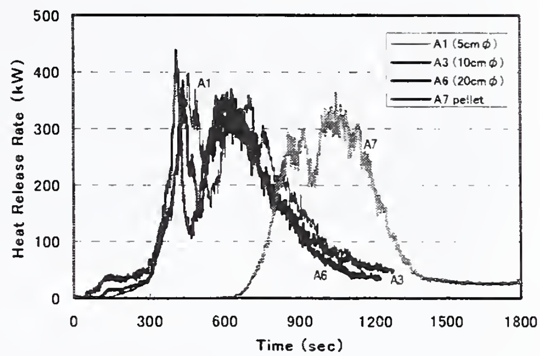
No.	Test Pallet [weight %]	Ignition Heat Source	PHR (kW)	time (sec)
A1		5cm φ 1)	398	458
A2		5cm φ	484	502
A3	Pallet-PP	10cm φ	385	436
A4	(non-FR treate	10cm φ	432	378
A5	PP)	20cm φ	401	492
A6		20cm φ	439	410
A7		tablet	363	775
A8		tablet	526	526
A9		tablet	752	651

No.	Test Pallet [weight %]	Ignition Heat Source	PHR (kW)	time (sec)
B1		5cm φ	83	1118
B2	Pallet 752	10cm φ	88	1144
B3		10cm φ	82	510
B4	($Mg(OH)_2$ [50]	20cm φ	108	661
B5		tablet	N/A.	N/A.
C1	Pallet 748	5cm φ	4	456
C2	(r-P[4.6]	10cm φ	5	218
C3	+$Mg(OH)_2$[50	20cm φ	25	1206
D1	Pallet 750	5cm φ	2	338
D2	(r-P[9.1]	10cm φ	5	266
D3	+$Mg(OH)_2$[50	20cm φ	31	448

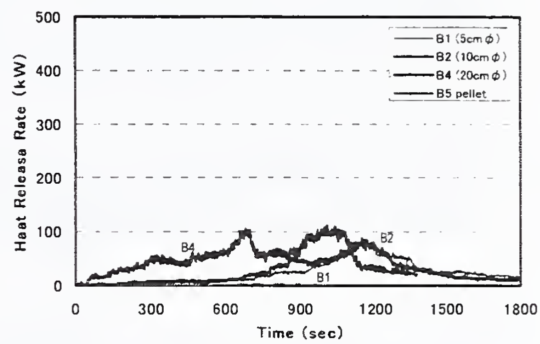
cf. 1) Value of ignition heat source is diameter of methenol pan.

Furniture calorimeter test result : Figure 7 and Table 3 show the heat release rate of the 1/4 piece of full scale pallet. In the case of the pallet made of base PP, the differences of ignition heat source do not affect the heat release rate. Heat release rate reaches to almost 450kw at first. Afterwards the heat release rate decreases while the plastic pallet is melting, then heat release rate increases again as a pool fire. When the solid tablet fuel is used as an ignition heat source, ignition time gets longer, however once it starts to burn, the combustion behavior appears to be nearly the same as in the cases of other ignition heat sources. The heat release rate of plastic pallets made of PP added with only $Mg(OH)_2$ is relatively low, however once it burns, the burning continues in spite of the size of ignition heat source. In contrast when r-P is added, the heat release rate becomes lower and the burning of the pallets can not be sustained without ignition heat source.

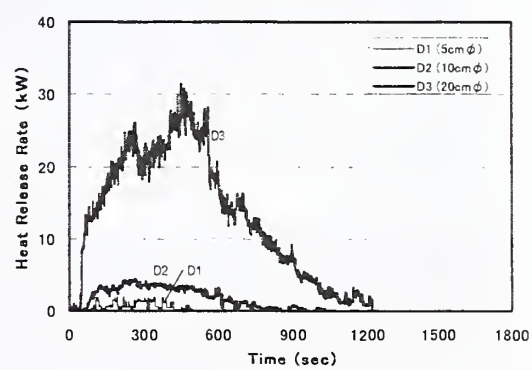
Mechanical properties : In this projects, mechanical properties of plastics have been examined by standard tests. The result indicates that "the flexural rigidity" of test pallets are about twice as strong as that of original non-FR treated pallets. "The sliding friction" of test plastic pallet does not change. However "the dropping impact test" results indicate that plastic of "EX-748" and "Ex-750" added with r-P are lower than that of standard ones. Also density of the developed plastic pallets is about 1.4 to 1.6 times heavier. These are remained for future tasks to be solved.



(a) Pallet -PP (non-FR treated poly-propyrene)



(b) Pallet 752 ($Mg(OH)_2$ [50])



(c) Pallet 750 (r-P.[4.6] + Mg(OH)2 [50])

Figure 7. Heat release rate of 1/4 piece of full-scale pallet by furniture calorimeter

CONCLUDING REMARKS

Development of fire-retardant plastic pallets has been conducted in collaboration with NRIFD and Association of plastic pallets and a fire retardant chemical company. Flammability and mechanical properties of some synthetic resins are examined in the two test stages to screen the material. The flammability of the resins are tested by cone calorimeter, UL94 and Oxygen Index Test. Finally appropriate combinations of $Mg(OH)_2$ and red-Phosphorus are selected as FR retardant additives. Major results obtained in the tests are as follows.

1) FR resins added with halogen containing retard the ignition time. However, once it burns, the FR effect decreases and more combustion products are generated.
2) In the case of FR resins added with magnesium hydroxide, the heat release rate and peak heat release rate become relatively low. Also combustion products are suppressed and mechanical properties satisfy practical requirements.
3) Red-Phosphorous additive has an effect on mitigation of the heat release rate, when it is used in combination with other FR chemicals. Single use of the r-P does not have a big FR effect and produces more combustion products.
4) In general the peak heat release rate decreases as the oxygen index increases as for non-halogen FR treated resin. When oxygen index is over 26, heat release rate becomes very low and the UL94 classification corresponds to "V0".
5) The prototype of FR plastic pallets is produced of the combination compound of $Mg(OH)_2$ and red-Phosphorus, and the fire test is conducted with furniture calorimeter. The FR effects of those plastic pallets are examined in full scale and sufficient FR effects are obtained with satisfaction. Along with the flammability tests, some of the mechanical properties are examined and a few mechanical properties are needed to be improved such as the dropping impact durability etc.

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HEAT RELEASE KINETICS

Richard E. Lyon
Fire Safety Section AAR-422
Federal Aviation Administration
William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405
richard.e.lyon@tc.faa.gov

ABSTRACT

The heat release rate in steady, flaming combustion is obtained from solid state thermal degradation kinetics using a simple models of polymer burning. Detailed thermal degradation chemistry is foregone in favor of a transient mass balance on the polymer, fuel gases, and solid char in the anaerobic pyrolysis zone. Closed-form, time-independent solutions for the scalar mass loss rate and char yield are obtained from the degradation kinetics which, in combination with the solid state heat transport provide the scaling relationship between material properties and steady burning rate.

FIRE BEHAVIOR OF COMBUSTIBLE SOLIDS

Once sustainable ignition has occurred, steady, one-dimensional burning of the thermally-thick polymer is assumed. Steady burning at a constant surface heat flux is treated as a stationary state by choosing a coordinate system which is fixed to the surface and moving at the recession velocity v as shown in Figure 1.

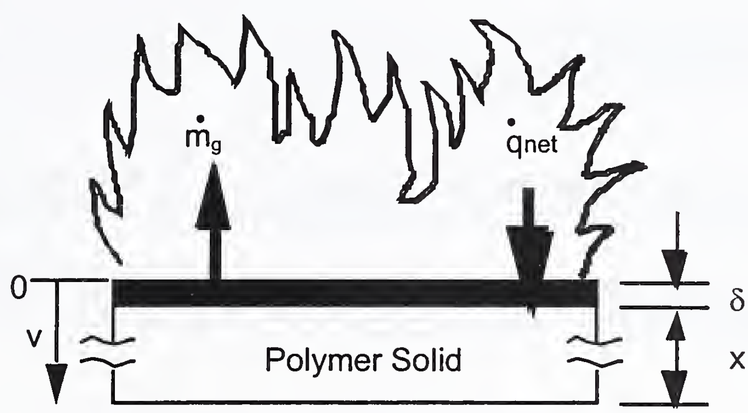

Figure 1. Geometry of Polymer Combustion Analysis

If there is no internal heat generation or absorption, the one-dimensional heat conduction equation applies

$$\rho c \frac{T}{t} - \rho c v \frac{T}{x} = \kappa \frac{{}^{2}T}{x^{2}} \tag{1}$$

where T is the temperature at location x in the solid polymer of thermal conductivity, κ, density, ρ, and heat capacity, c; and v is the regression velocity of the burning surface. Under steady-state conditions, dT(x)/dt = 0 and the pyrolysis zone of constant thickness δ moves through the infinitely thick solid with a fixed temperature gradient so that Equation 1 becomes

$$\frac{d^2T}{dx^2} + \frac{v}{\alpha}\frac{dT}{dx} = 0 \tag{2}$$

for steady burning of a material with a constant thermal diffusivity, $\alpha = \kappa/\rho c$. The solution for the temperature distribution is

$$T(x) = T_o + \left[\frac{\dot{q}_{net}}{\rho c v} - \frac{\Delta h_v}{c}\right]\exp\left[-\frac{v}{\alpha}x\right] \tag{3a}$$

or

$$T(x) - T_o = \left(T_p - T_o\right)\exp\left(-\frac{c\,\dot{q}_{net}}{\kappa\, h_g}\,x\right) \tag{3b}$$

for a steady recession velocity of the surface x = 0 at surface temperature $T(0) = T_s \;\; T_p$

$$v = \frac{1}{\rho}\frac{\dot{q}_{net}}{\left(c\,(T_p - T_o) + \Delta h_v\right)} = \frac{1}{\rho}\frac{\dot{q}_{net}}{h_g} \tag{4}$$

where $\dot{q}_{net}$ is the net surface heat flux, T_p is the peak mass loss (pyrolysis) temperature, and h_g is the heat of gasification per unit original mass of polymer[1]

$$h_g = c(T_p - T_o) + \; h_v. \tag{5}$$

Equation 3 is in qualitative agreement with experimental data[2] for the temperature gradient in steadily burning liquid pools if T_p is taken as the boiling temperature of the liquid fuel.

Conservation of mass for the control volume in which the virgin polymer of density ρ pyrolyzes to an inert or char fraction μ where μ = mass of char/original mass, gives

$$\rho v = \frac{\dot{m}_g}{1 - \mu} \tag{6}$$

where $\dot{m}_s$ is the mass loss rate of pyrolysis gases per unit surface area. Defining a heat of gasification per unit mass of volatiles

$$L_g = \frac{h_g}{1 - \mu} \tag{7}$$

and combining Equations 4, 6, and 7

$$\dot{m}_g = \frac{\dot{q}_{net}}{h_g/(1-\mu)} = \frac{\dot{q}_{net}}{L_g} \tag{8}$$

The heat of gasification per unit mass of solid polymer h_g can be determined from the reciprocal slope of a plot of areal mass loss rate *versus* external heat flux if the char yield μ is measured after the test, since

$$\dot{m}_g = \frac{\dot{q}_{ext}}{L_g} - \left(\frac{\dot{q}_{flame} - \dot{q}_{cr}}{L_g}\right) \tag{9}$$

Multiplying Equation 9 by the net heat of complete combustion of the volatile polymer decomposition products h_c^o and the gas phase combustion efficiency χ gives the usual result for the average heat release rate of a burning specimen[1],

$$\dot{q}_c = \chi h_c^o \dot{m}_g = \chi (1-\mu) \frac{h_c^o}{h_g} \dot{q}_{net} = \chi \frac{h_c^o}{L_g} \dot{q}_{net} \tag{10}$$

In the following kinetic development of the fuel generation rate from thermal degradation reactions it will be useful to know the rate of temperature rise at the surface as the pyrolysis zone moves through the solid at constant velocity, v. From Equations 6 and 7 the effective heating rate at the surface is

$$\left.\frac{dT}{dt}\right|_{x=0} = v \left.\frac{dT}{dx}\right|_{x=0} = \frac{\dot{q}_{net}^2}{\kappa\rho c\left(T_p - T_o\right)}\left(1 + \frac{\Delta h_v}{h_g}\right) \tag{11a}$$

where h_v is the heat of vaporization of the degradation products. Typically[3], h_v/h_g 0.1, so that to a good approximation the heating rate at the surface from Equation 11a is

$$\left.\frac{dT}{dt}\right|_{x=0} \approx \frac{1}{2} \frac{\dot{q}_{net}^2}{\kappa\rho c(T_p - T_o)} \approx \frac{\dot{q}_{net}^2}{\kappa\rho h_g} \tag{11b}$$

According to Equation 11b the rate of surface temperature rise of a polymer with T_p 500°C (723 K) and a typical $\kappa\rho c = 5 \times 10^5$ W-s-m^{-4}-K^{-2} experiencing a 50 kW/m^2 net surface heat flux is dT/dt = 5 K/s.

FUEL GENERATION KINETICS

The first stage of thermal degradation at a burning surface produces primary volatiles (gas and tar) and possibly a primary char residue. If a primary char forms, further decomposition occurs by dehydrogenation to form the secondary gas (principally hydrogen) and a thermally stable secondary carbonaceous char as illustrated schematically in Figure 2.

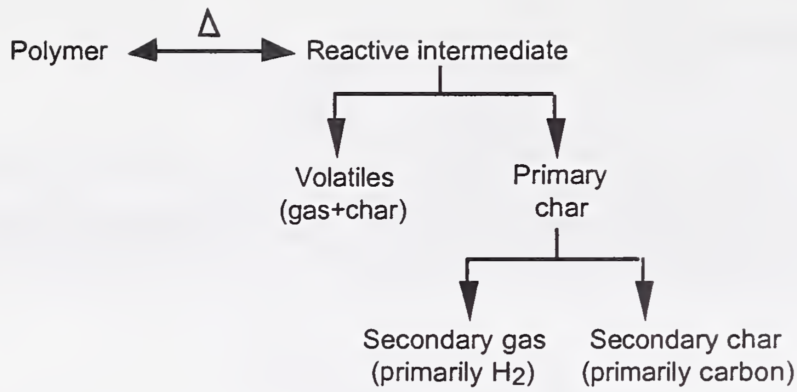

Figure 2. Generalized Thermal Degradation Mechanism of Polymers

A simple, solid-state fuel generation model has been derived[4] from Figure 2 with the following assumptions about the process of polymer thermal degradation as it occurs in fires:

1. A reactive intermediate I* is generated in the polymer dissociation (initiation) step which is in rapid dynamic equilibrium with the parent polymer, P, but is consumed in the process of gas and char formation such that its concentration never becomes appreciable and decreases slowly over time as the polymer is consumed. This is the stationary-state hypothesis.

2. For practical purposes, thermal decomposition can be treated as a single step process[5].

3. The thermal degradation environment in the pyrolysis zone of a burning solid polymer is non-oxidizing or anaerobic. Dissolved molecular oxygen and oxygen diffusion into the pyrolysis zone of the solid are considered negligible with respect to their effects on gas and char formation so that solid-state oxidation reactions can be neglected in the fuel generation model for polymers in fires.

Figure 3 shows data[3] for a variety of pure, unfilled polymers plotted as the char yield measured after flaming combustion in a fire calorimeter *versus* the char residue at 850-900°C for the same material after anaerobic pyrolysis. It is seen that the char yield of a material in a fire is essentially equal to its residual mass fraction after pyrolysis in an oxygen-free environment at temperatures representative of the char temperature in a fire. Although oxidative degradation products have been identified at the surface of noncharring olefinic polymers after flaming combustion [6,7], the close agreement between fire char yield and anaerobic pyrolysis residue in Figure 3 suggest that oxidation reactions are insignificant in the char formation process as it occurs in the pyrolysis zone of a burning polymer.

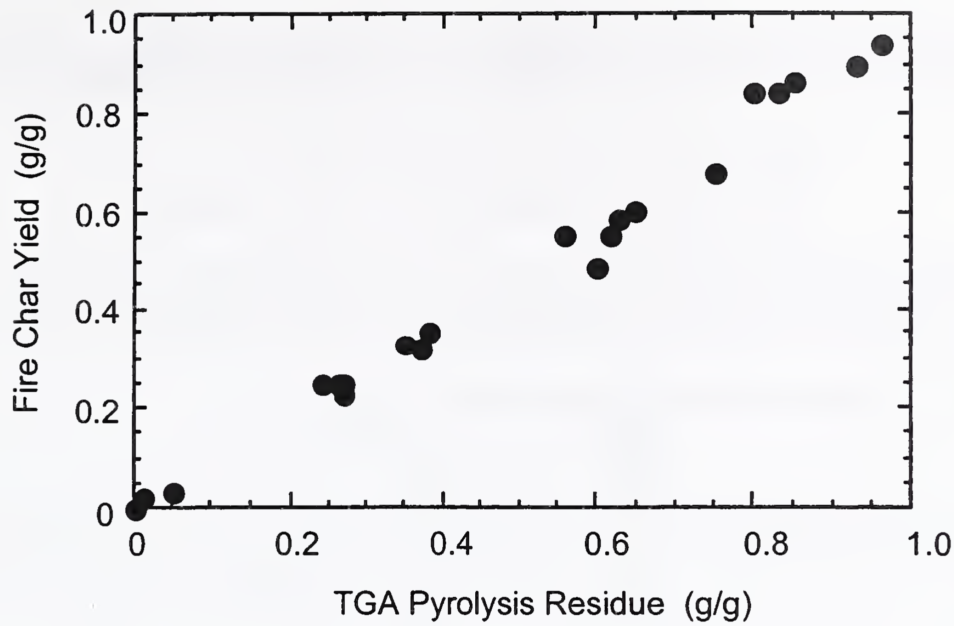

Figure 3. Fire Char Yield *versus* Anaerobic Pyrolysis Residue for a Variety of Polymers

The generalized combustion and pyrolysis scheme of Figure 2 in combination with assumptions 1–3 lead to the simplified kinetic model for polymer combustion shown in Figure 4.

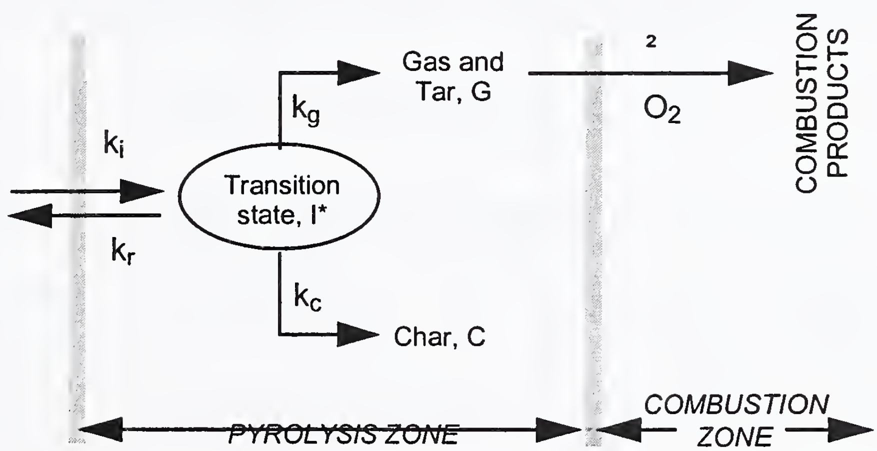

Figure 4. Thermal Degradation Model for Polymers in Fires

This simplified scheme reduces thermal degradation of polymer P to a single step involving parallel reactions of an active intermediate I* to form to gas G and char C. In Figure 5, k_i is the rate constant for initiation, and k_r, k_g, and k_c are the rate constants for termination by recombination (k_r), hydrogen transfer to gaseous species (k_g), and crosslinking to char (k_c), respectively. Neglecting solid-state oxidation the thermal decomposition reactions are

$$P \underset{k_r}{\overset{k_i}{\rightleftharpoons}} I^* \qquad \textit{(rapid equilibrium)} \qquad (12)$$

$$I^* \xrightarrow{k_g} G \qquad \textit{(slow)} \qquad (13)$$

$$I^* \xrightarrow{k_c} C \qquad \textit{(slow)} \qquad (14)$$

and the system of rate equations for the species at time, t, is

$$\frac{dP}{dt} = -k_i P + k_r I^* \qquad (15)$$

$$\frac{dI^*}{dt} = k_i P - \left(k_r + k_g + k_c\right) I^* \qquad (16)$$

$$\frac{dG}{dt} = k_g I^* \qquad (17)$$

$$\frac{dC}{dt} = k_c I^* \qquad (18)$$

According to the stationary-state hypothesis, $dI^*/dt \quad 0$ so that Equation 15 provides the useful result

$$I^* = \left[\frac{k_i}{k_r + k_g + k_c}\right] P = K\,P$$

where $K = k_i/(k_r + k_g + k_c)$ is the pseudo-equilibrium constant for the polymer dissociation reaction. The isothermal solution of Equations 17-20 is straightforward[4].

Solution of Equations 15-18 for $dI^*/dt \quad 0$ at a constant heating rate $\beta = dT/dt$, gives for the extent of polymer reaction at temperature T

$$\frac{M(T)}{M_o} = Y_c(T) + [1 - Y_c(T)]\, e^{-y} \qquad (19)$$

where M_o is the initial mass,

$$y = \frac{A}{\beta}\int_{T_o}^{T} \exp\left(-\frac{E_a}{R\theta}\right) d\theta \approx \frac{ART^2}{\beta\,(E_a + 2RT)} \exp\left(-\frac{E_a}{RT}\right) = \frac{k_p\, RT^2}{\beta(E_a + 2RT)}$$

and

$$Y_c(T) = \frac{M(\infty)}{M_o} = \frac{k_c}{k_g + k_c}$$

is the *equilibrium* residual mass fraction or char yield at temperature T in terms of the rate constants for gas k_g and char k_c formation. The overall rate constant for thermal degradation is

$$k_p = k_i - Kk_r = K(k_g + k_c) = A\exp\left(-\frac{E_a}{RT}\right) \tag{20}$$

in terms of the global activation energy E_a and frequency factor A for pyrolysis. Differentiating Equation 19 twice with respect to time at constant heating rate gives an expression for the peak mass loss rate

$$\frac{-1}{M_o}\frac{dM}{dt}\bigg|_{max} \approx (1-\mu)\frac{\beta E_a}{eRT_p^2} \tag{21}$$

Multiplying Equation 21 by the heat of complete combustion of the volatile thermal degradation products h_c^o gives the time-independent (peak) kinetic heat release rate at constant heating rate β

$$\dot{Q}_c(\mathrm{W/kg}) = -h_c^o\frac{\dot{M}_{max}}{M_o} \approx h_c^o\frac{\beta(1-\mu)E_a}{eRT_p^2} \tag{22}$$

Substituting Equations 20 and 3 into Equation 10, it can be shown that the steady macroscopic heat release rate per unit area of burning surface for a pyrolysis zone thickness δ (see Figure 1) is[8]

$$\dot{q}_c(\mathrm{W/m^2}) = \chi h_c^o\langle\dot{m}_g\rangle = \chi h_c^o\int_0^\delta \rho_g k_p(x)\,dx = \chi\rho\delta\left(h_c^o\frac{\dot{M}_{max}}{M_o}\right) = \chi\rho\delta\dot{Q}_c \tag{22}$$

from which the ratio of the macroscopic and kinetic heat release rates at comparable surface heating rates is

$$\frac{\dot{q}_c}{\dot{Q}_c} = \chi\rho\delta \tag{23}$$

Thus, proportionality between the macroscopic heat release rate and the kinetic heat release rate depends on the product of the gas phase combustion efficiency χ, polymer density ρ, and pyrolysis zone thickness δ. The pyrolysis zone thickness can be estimated using the criteria that the mass loss rate falls to 1/e of the surface (x = 0) value at 1/e of the pyrolysis zone thickness $x = \delta/e$. The result is [3,8]

$$\delta = \frac{\kappa}{\dot{q}_{net}}\frac{eRT_p^2}{E_a} \tag{24}$$

For typical polymer values $T_p = 750$ K, $E_a = 200$ kJ/mol, and $\kappa(T_p)$ 0.2 W/m-K, Equation 24 predicts δ 0.3 mm at a net incident heat flux, $\dot{q}_{net} = 50$ kw/m^2, which is in agreement with estimates[2,9] δ 1 mm.

A rate-independent flammability parameter comprised only of material properties emerges from this analysis when the kinetic heat release rate $\dot{Q}_c$ (Equation 22) is normalized for heating rate

$$\eta_c \equiv \frac{\dot{Q}_c}{\beta} = \frac{h_c^o (1-\mu) E_a}{eRT_p^2} \tag{25}$$

The thermokinetic flammability parameter η_c has the units (J/g-K) and significance of a heat [release] capacity when the linear heating rate is β(K/s). Substituting the heat release capacity η_c (Equation 25), pyrolysis zone depth δ (Equation 24), and surface heating rate β (Equation 11) into Equation 22 recovers the steady heat release rate in flaming combustion (Equation 10) from the thermochemistry after cancellation of terms

$$\dot{q}_c = \chi\rho\delta\beta\eta_c = \chi\rho\left[\frac{\kappa}{\dot{q}_{net}}\frac{eRT_p^2}{E_a}\right]\left[\frac{\dot{q}_{net}^2}{\kappa\rho\, h_g}\right]\left[\frac{h_c^o(1-\mu)E_a}{eRT_p^2}\right] = \chi\frac{h_c^o}{L_g}\dot{q}_{net} \tag{26}$$

Obtaining the macroscopic heat release rate from the derived diffusion (β) thermokinetic (η_c) and coupling (δ) parameters shows that the present thermochemical treatment of steady burning is self-consistent.

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A STUDY OF THE EFFECTIVENESS OF FIRE RESISTANT DURABLE AGENTS ON RESIDENTIAL SIDING USING THE ICAL APPARATUS

Arthur F. Grand
Omega Point Laboratories, Inc.
16015 Shady Falls Road
Elmendorf, Texas 78112–9784

ABSTRACT

A test protocol based on the Intermediate Scale Heat Release Calorimeter (ICAL) was developed to evaluate the potential fire retardant effects of water-based durable agents applied to wood siding. The protocol includes exposure of one meter square specimens of siding to one or more constant heat fluxes consistent with those from wildland fires. Specimens both untreated and treated with a fire-retarding gel have been evaluated in a preliminary study. Time delay to ignition of the treated specimen was the primary measured property, while mass changes prior to and during the fire exposure were also recorded. A more comprehensive study is presently underway.

INTRODUCTION

Wildland/urban interface fires are a unique problem in fire research and testing. Generally, fires in buildings begin inside, rather than outside, the structure and most standard test protocols reflect that. One exception is NFPA 268 which deals with the issue of flammability of siding in commercial buildings. In that method, specimens are exposed to a 12.5 kW/m^2 radiant flux in order to simulate proximity to another building on fire. The wildland fire environment is not normally considered in evaluating structures, especially residential housing. While "permanent" fire retardant treatments and coatings exist, it would be impractical to treat the exteriors of all houses to be resistant to wildland fires. However, temporary treatments, such as water-based fire retarding agents, have been used to protect structures during such fires.

There are two primary means of attack on a structure by a wildland fire, radiant heat and burning brands. In the case of radiant heat, a heat flux above about 25 kW/m^2 will ignite wood structures, even without a specific ignition source. Heat fluxes as low as about 15 kW/m^2 will also ignite wood siding in the presence of a suitable ignition source. Burning brands tend to collect in protected areas of a house, such as under eaves and in corners. These brands could be sufficient to start a fire along the exterior of the house. Without any protection or treatment, the wood structure would continue to burn.

Recently, durable agents and water-based gels have been used to protect homes against the threat of wildland fires[1]. Without any standards, or even very much research, it is difficult to demonstrate the efficacy of these agents. Internal research studies at

BFRL/NIST[2,3] included treatment of wood siding and exposure to moderately high intensity fire sources. A recent study at Omega Point Laboratories, Inc.[4], sponsored by NIST, was a preliminary program to determine the feasibility of using the ICAL test method (ASTM E1623) to characterize the efficacy of temporary, spray-on fire retardant treatments for wood siding.

TEST APPARATUS

The standard ICAL apparatus and test method (ASTM E1623) were used for this study, with certain modifications as listed below:

1) A specimen support frame was developed to permit presentation of the complete surface area of the specimen, both for treatment and for exposure to the radiant heat (see Figure 1). The specimen was held in place by clamps in each of the four corners.

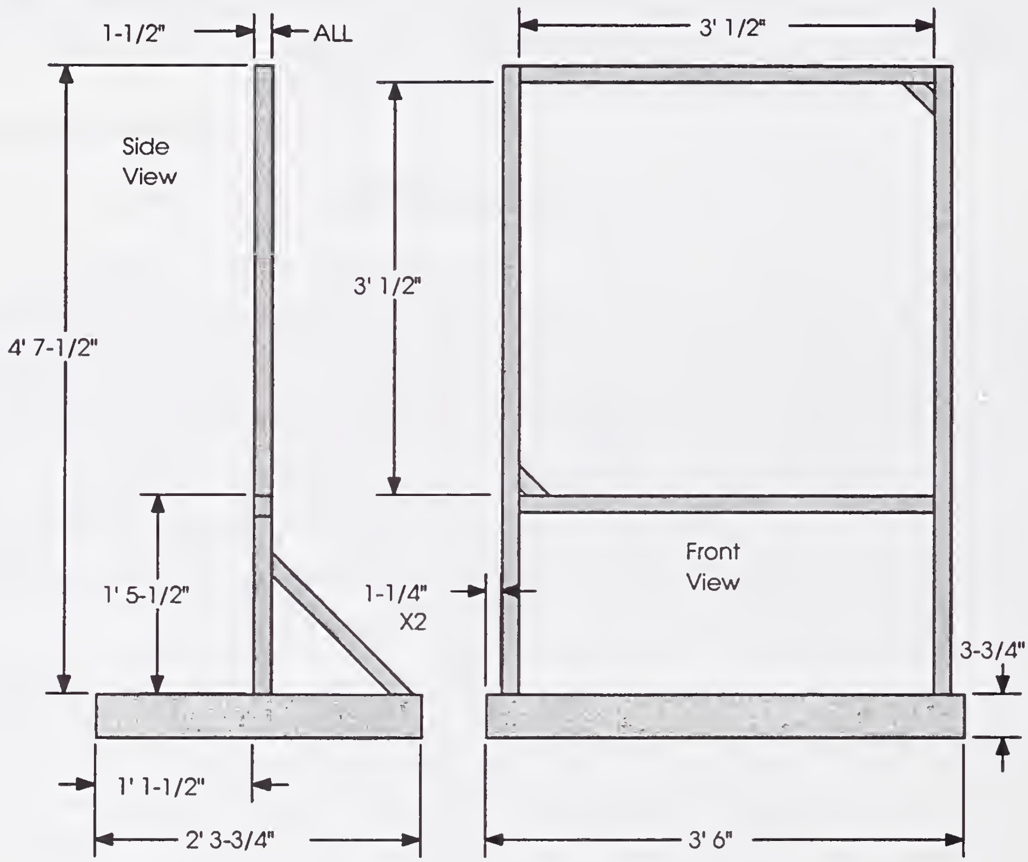

Figure 1. Specimen support frame for plywood siding

2) An open-flame burner was adapted from another test method (see below).

3) The ICAL radiant panel was calibrated to the range of heat fluxes required, from a maximum of 25 kW/m^2 to as low as "Texas summer sun" heat fluxes (ca. 1 kW/m^2).
4) The actual fire exposure was conducted for as long as necessary to evaluate the efficacy of the coating. Generally, the experiments were terminated upon ignition and continued burning of the specimen.
5) Heat release rate (HRR) was not determined in these experiments. It was reasoned that the experiment was essentially over once the HRR reached a measurable level. Mass loss was monitored prior to ignition.
6) Application of the coating and allowance for an extended drying period were performed with the radiant panel operating and open to the specimen (at heat fluxes estimated at 1-3 kW/m^2). The higher flux exposure was begun by moving the specimen to a pre-determined distance from the panel and lighting the pilot burner.

A propane "T" burner, from the mattress test method California Technical Bulletin 129, was used as the pilot ignition source. The burner was positioned approximately two inches (50 mm) from the bottom of the specimen, in the center, and approximately eight inches (200 mm) from the surface of the specimen. The pilot flames were near to, but not in direct contact with, the surface of the specimen.

The following materials were used in this study:

Plywood siding: T1-11, 10 mm (3/8 in.) thick, obtained locally (Home Depot)

Red latex exterior flat paint: obtained locally (Home Depot); a single, heavy coat was applied

"Barricade®" Fire-Blocking Gel concentrate: supplied by Fire Protection, Inc., Jupiter FL (contact person: John Bartlett, 561/575-6055)

Delivery system for the gel was a "Home Protection AtakPak": supplied by Fire Protection, Inc.; this included a nozzle, hose, eductor and quick disconnect. This equipment was used to aspirate the gel into the water stream and to deliver the mixture through an adjustable water-spray nozzle.

RESULTS AND CONCLUSIONS

The results on times to ignition for the preliminary study are summarized in Table 1. Several different treatments and two heat fluxes were tried during that series of tests. It can be seen from the data in the table that the painted and unpainted wood siding behaved similarly, except that the effect of water alone may have been greater for the unpainted wood. This could be attributed to greater water pick-up for the unpainted siding. There was relatively little control of the application rate or the ratios of the gel/water mixtures; therefore, few tests were conducted with the gel in the preliminary series. However, the potentially dramatic effects of treatment by the gel are evident from the results obtained (i.e., up to about 1000 s for ignition, compared to around 100 s for water alone).

Table 1. Summary of Times to Ignition Results for Various Treatments and Substrates

Heat Flux (kW/m^2)	Condition or Treatment[a]	t_{ig} (s)[b] Unpainted	t_{ig} (s)[b] Painted
25	no treatment, no pilot	614	525
25	no treatment	74	82
25	water spray	125	91
25	gel (light), 60 min. dry	211	
25	gel (heavy)	1092[c]	923[c], 941[c]
15	no treatment, pilot	221	134
15	water spray	200	171
15	water spray, dry 60 min.	85	

a) pilot burner present unless otherwise noted

b) T_{ig} = time to ignition (sustained for at least 10 s, unless otherwise noted)

c) ignition was achieved, but flames went out quickly and never progressed to flaming across the surface of the specimen, as in the other cases

Mass determinations were conducted to determine the water or gel/water pick up prior to the test and the mass loss during the preliminary exposure of the specimen (i.e., up to ignition). These results confirmed the high dose of the gel in some experiments (up to 5 lbs/ft^2) and the greater pick up of water by the unpainted wood (approximately 0.1 – 0.2 $lbs./ft^2$) compared to the painted wood (0.05 $lbs./ft^2$). The high pick up of the water in the gel mixture was evident by the mass data, compared to the water spray alone. Mass loss rates for the specimens prior to ignition were also measured.

The primary result of the studies to date are that the ICAL apparatus appears to be suitable for evaluating the response to heat and flame of wood siding with certain applied, temporary surface treatments, including a water-based durable agent and water alone. Satisfactory tests were conducted at both 25 kW/m^2 and 15 kW/m^2 heat flux. The repeatability of ignition of common plywood siding with or without a pilot burner was acceptable under the preliminary protocol. As a result, we generally were able to observe a delaying effect of water treatment alone on the ignition of wood paneling. Although this effect was small, it opens the possibility for a simple internal laboratory calibration test as part of a final protocol.

The "Barricade" gel treatment applied to wood siding in the preliminary study yielded promising results in terms of delayed ignition, even at a heat flux of 25 kW/m^2. Further evaluation of this and other treatments is underway in the current study.

Drying under low heat flux conditions, prior to a higher heat flux exposure, was achievable using this experimental setup.

PRESENT STUDIES

A number of issues are being addressed in the study currently underway. Measurement and control of the mixing of the concentrated agent and water must be improved over that in the preliminary study. Such information will permit establishment of comparable application rates for various coatings and to evaluate the performance of any given coating at various applications.

Both higher and lower heat fluxes than the 25 kW/m^2 will be examined for both screening and standard testing purposes. An applied heat flux of 25 kW/m^2 was sufficient to ignite wood without a pilot flame and seems suitable for evaluating most agents. Shorter duration, high flux exposures will be used to characterize the performance of certain better quality agents, while lower flux exposures may help in the development of research data to potentially improve the performance of marginally acceptable agents.

In addition to wood siding, other substrates will include plastic siding and glass windows in a wood framework. The ability of the coating to adhere to these substrates and the ultimate performance of the coating on surfaces other than wood will be considered.

Various water-based coatings will be exposed to lengthy periods of drying under "summer sun" conditions in order to determine the effect of drying on fire performance. Such atmospheric conditions are realistic and are expected to play a role in the suitability of temporary coatings.

Thermocouples will be placed between the gel coating and the wood surface for selected experiments in order to provide input for modeling and for prediction of the efficacy of the coating as a function of coating thickness. Calculation of an effective thermal conductivity for the coating should be possible.

In order to measure any significant heat release rate over that of the combined HRR of the radiant panel and the igniter, the specimen would have to be burning vigorously and the coating has failed. This is easy to detect visually and generally signifies the end of the test. Therefore, measurement of HRR, while always an option, need not be done for these experiments. Mass loss measurements could always be used to estimate rate of burning, if needed. Several potential fire scenarios can be simulated by the modified ICAL radiant panel method described herein. These include the following: burning brands up against the siding (e.g., 20 kW/m^2, with pilot burner), burning shrubbery near the house (e.g., 25-35 kW/m^2, with pilot burner), mild to moderate radiant heat from a wildland fire (10-20 kW/m^2, without pilot burner), intense radiation for a relatively brief duration (up to 50 kW/m^2, with or without the pilot burner).

Criteria for acceptability will be considered, based on the results of this study. Such criteria might include delay in times to ignition at a fixed heat flux, reduction in the extent of burning across the surface once ignition occurs, protection of the substrate to short intervals of higher heat flux, and extended protection of the substrate to longer duration exposures at moderate heat fluxes.

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PEOPLE AND FIRE

OVERVIEW OF RESEARCH ON PEOPLE AND FIRE IN THE U.S.

John R. Hall, Jr., Ph.D.
National Fire Protection Association
Quincy, MA 02269-9101

ABSTRACT

Research on people and fire in the U.S. has recently emphasized practical application over new research. Work continues on several types of evacuation models, but their use in engineering analysis lags behind the state of the art. There is little new modeling or data work in the field of toxicity and other fire effects on people. International efforts to write standards for fire hazard assessment, however, have resulted in much controversy over such details as societal safety objectives and the reasonableness of alternative assumptions, at the fringes of what is known, regarding fire effects on people. These controversies may lead to important new research but for now are being debated with considerable use of non-peer-reviewed data.

INTRODUCTION

Since the last UJNR meeting, research and related work in the U.S. on topics of people and fire have tended to emphasize issues in the practical application and standardization of knowledge gained in prior decades. Both the field of people's reaction to fire (i.e., human behavior) and the field of fire effects on people (e.g., toxicity) also have shown an increasing globalization, with a high degree of international collaborative work and international debate over best ways to interpret and apply past research.

This emphasis on issues of practical application has had a side effect of moving much of the current and recent research from conventional outlets such as peer-reviewed journals and conferences to more advocacy-oriented forums, such as private communications in support of recommended actions on standards. This shift becomes troublesome if it becomes clear that important issues have not yet been settled and fully resolved in the peer-reviewed scientific literature. Such has been the case in recent years for the toxicity issue.

EVACUATION MODELING AND OTHER HUMAN BEHAVIOR

There continue to be three principal types of evacuation models in use and in development in the U.S. and around the world. The oldest type is an optimization type model, which is used to calculate the most efficient paths of escape and thus the shortest evacuation times achievable. This approach, which used to be dominant, has now almost disappeared. In recent work, the only U.S. example identified is by Kostreva and Lancaster [1]. Their multi-objective dynamic programming model has the same advantages and disadvantages as other models of this type. It can be useful to know the

best achievable time but principally as a basis for evaluating more realistic predicted times. This model cannot itself provide realistic predicted times. It can be useful for building design and exiting guidelines to identify efficient escape paths that are not obvious. However, the actual modeling of evacuation behavior remains.

The second type of evacuation model is a node-and-network approach, in which all knowledge and data regarding human exiting behavior is channeled into a small number of variables that dictate exiting choices and speeds of movement along the network. This approach describes actual behavior rather than ideal behavior and is flexible enough to be improved when better data or better understanding of underlying human behavior becomes available. A recent paper within this approach is by Rita Fahy, describing improvements to her model EXIT89 [2]. Ms. Fahy also will present recent work in this area at greater length later in this UJNR symposium.

The third type of evacuation model is a fine structure simulation, which compares to the simpler node-and-network approach as a computational fluid dynamics model of fire development compares to a simpler zone model. That is, the underlying logic of the two approaches is essentially the same, but the much finer structure of the simulation approach creates a model so different in scale that it may be considered different in kind. Rather than a network built on a relatively small number of nodes, each representing a sizeable space, the fine structure simulations use a grid representation. The best known of these simulations are outside the U.S., but one such approach was developed by Feinberg and Johnson, two sociologists at the University of Cincinnati [3]. While the fine structure of the simulation approach appears to offer a more precise model of behavior, at present the lack of proven behavioral models and relevant data forces all the simulation approaches into extensive use of heuristic methods, empirically inferred relationships, and subjectively estimated data. The theoretical advantages of the modeling framework in the simulation approach, therefore, are today more than fully offset by unanswerable questions about the modeling components and the input data.

A common weak point for all current evacuation models is data and knowledge regarding human behavior other than movement toward an exit, where only distance, ability to move, congestion, the building layout, and other such straightforward, observable phenomena are involved. In just the past couple years, Bryan [4] provided a summary overview of the history of the field of human behavior in the face of fire, and his closing remarks pointed to the need to revisit certain commonly used but questionable assumptions, such as the assumptions implicit in using exit drill behavior and speeds, unmodified, to model exiting behavior and speed under real fire conditions. Ozel [5] studied the effect of stress and time pressures on decision-making for evacuation. Lynch [6] studied olfactory response to combustion products as a stimulus that may provide first indication of fire. His experimental results confirmed the view embedded in current safety advice that olfactory response will only rarely arouse a sleeping person. And in two papers, Groner [7,8] continued to refine and advance his view that evacuating people

must be modeled as purposeful decision-makers rather than ballistic objects or rule-bound robots.

Except for Lynch, these researchers provided more questions than answers and stopped short of providing any new data or mathematical relationships that could be used to improve modeling of evacuation. Researchers in Canada and Northern Ireland, and to a lesser extent Australia, have done more than those in the U.S. to develop and disseminate new data. However, the net effect of current work has been a proliferation of new variables whose values must often be determined subjectively and whose relationships to other variables can only be empirically determined by fitting to a generic multi-factor statistical model.

A fundamentals-based set of primary equations – what one might call the Newton's Law of human behavior – has so far remained elusive, and only recently have there been even fitful indications that some key researchers see the need to look for such equations. This has not prevented the current models from demonstrating an ability to provide useful answers and to accurately predict evacuation times in a wide range of drills and reconstructed fire situations. The models pass the test of what constitutes science; they are subject to disproof by empirical data, and when tested against such data, they provide good predictions.

Also, current practice in the field of fire safety engineering has made very little use of the models that already exist. An engineering analysis by Crowley [9] is a rare published example of the common pattern that engineers either ignore evacuation entirely or model it based on distance and speed only, using readily available speeds for typical occupants. These analyses ignore congestion, variations in human abilities including the special problems of the disabled, and, most importantly, pre-movement times, which are frequently larger components of total evacuation times than the times required for movement.

Fahy and Sapochetti [10,11] issued strongly worded calls to engineers to do better and to recognize the dangers of current practice. The simplified approach to evacuation will tend to understate, often greatly, the time required for evacuation, which means the time during which occupants are exposed to fire effects is also understated. The resulting analysis is not safely conservative or even a prediction on the averages; it is optimistic, which is not an acceptable basis for fire-safe design. Meacham [12] has also provided ideas and approaches on how human behavior factors can be better integrated into engineering analysis.

Some papers on people and fire do not fit neatly into a focus on evacuation behavior. Waters [13] analyzed all the time components from ignition to effective fire suppression. His purpose was to demonstrate that, despite the fact that this objective is often at the center of fire service planning for staffing and company deployment, fire brigades cannot expect to arrive before flashover occurs at a structure fire. Even if travel time can be

reduced to zero, other time components will make that objective unachievable in many, perhaps most, structure fires with flashover potential. This finding indirectly affects work on evacuation modeling, because it removes one of the rationales by which analysts have sometimes sought to minimize the importance of evacuation time in fire safety planning. If early control of fire by the public fire service cannot be reliably, let alone affordably, achieved, then on-site protection and protocols must be sufficient to achieve safety objectives.

Beller and Watts [14] provided ideas on the use of current knowledge regarding human capability and behavior, focusing on observable conditions, to develop improved occupancy classifications for use in building and fire codes. These classifications are used now to simplify the matching of fire protection to the occupants' levels of need. So long as such classifications remain necessary – which means so long as unconstrained performance-based design remains a rarity – ideas like Beller's and Watts' will be useful to improve practice. Jennings [15] provided a literature review of decades of studies of the link between socioeconomic characteristics and fire risk.

FIRE EFFECTS ON PEOPLE

Babrauskas et al. [16] published an overview of the Fractional Effective Dose (FED) approach to the assessment of fire effects on people, using the additive N-gas modeling structure, in which the effects of different combustion products are assessed individually, using threshold dose values in comparison to cumulative doses for individuals. Hartzell [17] provided a summary of the International Standardization Organization (ISO) draft protocol for assessment of toxic hazard, which is a particular application of the FED approach.

In keeping with the content of these two papers, most recent U.S. work in the area of fire effects on people has not been designed to provide new data or new mathematical relationships for modeling. (The Babrauskas reference provided a comprehensive description and rationale of a procedure that had already been described in more fragmentary terms in the literature and used for analysis for a number of years.) Instead, the research has been designed to address the key assumptions in the ISO approach, including many assumptions that are either unsubstantiated or actually counter to the best evidence in the U.S. research literature.

Among the key assumptions, captured in Hartzell's article, are these: (a) Basic FED approaches use thresholds that will injure or kill half the population (which is true), and a large multiplicative safety margin is required to adjust the threshold to protect an acceptably large fraction of the population (which is controversial). (b) Basic FED approaches use thresholds based on animal experiments (which is true), and a substantial multiplicative safety margin is required for inter-species conversion (which is controversial). (c) The toxic hazard of a burnable item is best measured by the combustion products it generates rather than the harmful environment it delivers to the

locations where potentially exposed occupants may be located. This overlooks the mitigating effects of transport, which are especially important in the U.S., where most fatal fire victims are located in a different room than the room of fire origin. (d) Safety objectives are or should be not simply to prevent death but to prevent incapacitation that could lead to death and to prevent any other significant acute or chronic health effects. This objective is far more ambitious than the goals stated in typical building and fire codes, the assumed close link between incapacitation and death is at best unproven and controversial, and the current state of knowledge regarding thresholds for sub-lethal effects has more gaps than proven values.

A particular issue within the larger context is the proposition that post-flashover fire situations are the dominant scenarios of concern and that carbon monoxide is so dominant in these situations that no other fire effects need be considered in predicting and assessing fire hazard. Hirschler [18] provided an extended discussion of the literature in support of this notion, with emphasis on the primacy of post-flashover fires. Nelson [19] provided an analysis of carbon monoxide as a lethal fire effect that also provides some support for this proposition.

As we meet at UJNR, efforts are underway to sponsor significant new research in the U.S. on sub-lethal effects. The ISO approach relies principally on claims made by researchers in the United Kingdom, including a heavy reliance on work that has not been submitted to peer review. Because of the time pressures involved in debating and voting on draft international standards, much of the recent U.S. work designed to respond to the U.K. data has itself bypassed the peer review process, at least for now. This is an unfortunate trend, as it jeopardizes our ability to use proven science and data that have the support of the full scientific community as the principal basis for the writing of codes and standards.

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PROGRESS AND OVERVIEW OF STUDY ON EVACUATION SAFETY AND FIRE RISK ASSESSMENT IN JAPAN

Manabu EBIHARA
Izumi Research Institute, Shimizu Corporation
2-2-2 Uchisaiwai-cho, Chiyoda-ku, Tokyo 100-0011, JAPAN

Ai SEKIZAWA
National Research Institute of Fire and Disaster
3-14-1 Nakahara, Mitaka, Tokyo 181-8633, JAPAN

INTRODUCTION

Recent studies in Japan regarding evacuation safety and fire risk assessment are encouraged in developing performance-based design method and performance assessment method, in common with the other fields of the fire safety engineering. Researchers and engineers are now preparing tools and methods that will be applicable to fire safety design based on the performance-based code, because the performance-based code for the building regulation will be enforced in June, 2000 in Japan. In this paper, the studies and papers regarding evacuation safety and fire risk assessment in Japan mainly from 1997 to 1999 are reviewed, and the future issues are discussed.

EVACUATION SAFETY

In the studies for evacuation safety assessment, there was a performance assessment method for egress routes [1, 2]. In this study, they turned their attention to assess legibility that means how evacuees can easily find or understand egress routes. The legibility is considered one of important performance required for egress route design in performance-based code. In this method, they assess the legibility using an expected travel distance to safety zone, for example a fire escape staircase, as an index. And, the studies have been conducted to assess the safety level of egress route in consideration of the reliability of fire protection systems that are required for egress routes [3, 4].

There is another kind of risk assessment method for evacuation [5, 6]. In these studies, an expected number of evacuees remaining in a space at the critical egress time is treated as an index, while the dispersion of evacuation starting time, number of evacuees, and difference of fire conditions are considered as parameters. The new simplified calculation method for evacuation behavior is proposed [7] to aim at practical use as an assessment tool for evacuation safety design based on the performance-based code.

Regarding fire safety design method, there are studies to aim at realizing an effective evacuation planning, especially for egress route design, based on psychological characteristics of evacuees, such as inclination of choosing a wider or lighter passage in evacuation [8~11].

There are some guidelines and provisions for the evacuation safety design that are described in the prescriptive building code in Japan. In the study for the evacuation safety code, alternative concepts of the prescriptive codes are represented from the viewpoint of making the performance-based code [12, 13]. There are other papers that introduced the fire safety engineering tools for evacuation applicable to the design based on the performance-

based code [14, 15].

Studies to investigate the evacuation behavior at real fires were presented [16~19]. And, we also had the studies to understand psychological characteristics of the evacuees by observing a change of heart rate or using a virtual reality simulator [20, 21].

The study on the evacuation behavior of the elderly and handicapped-persons is necessary [22~26]. In this regard, simulating evacuation behavior in a hospital or a facility for the elderly were presented [27~29]. In these simulation models, it is very important how to model the assistance action to disabled occupants by staff.

FIRE RISK AND FIRE RISK ASSESSMENT

Fire safety regulation has been changed several times depending on the social requirement, especially after the occurrence of serious or remarkable fires. The amendment of the fire safety regulation on fire protection measures was investigated to study its effect on fire risk [30].

The Tokyo Fire Department collects the data of fire protection systems based on an annual inspection to buildings. Using this data, the reliability of fire protection systems is discussed [31, 32]. In these papers, it was reported that the reliability of fire protection systems is decreasing along with the secular change. Also, the Tokyo Fire Department intends to develop the fire risk assessment method in consideration of the reliability of both fire prevention actions performed by security staff and fire protection systems. In relation with this project, several studies [33~36] were conducted.

On the other hand, the cost-effectiveness of fire protection systems is discussed from the viewpoint of evacuation safety [37, 38]. Regarding fire risk, the study to describe the relationship between fire risk and cost of fire protection systems [39], and the risk transfer for the external hazards and the internal hazards from the viewpoint of the property/casualty insurance [40] are conducted. And also, the issues of fire safety task from the viewpoint of risk management of buildings are discussed[41]. In Japan, there have not been so many studies regarding analysis on the relationship between fire risk and cost, or the fire risk management, but there is increasing necessity to discuss about this issue in the future. Furthermore, the study to discuss the mitigation of fire and fire deaths based on the recent statistical data of residential fires is reported [42].

CONCULUSIONS AND FUTURE ISSUES

In the background of movement toward the performance-based building codes in Japan, there are a number of studies on fire risk assessment and performance-based design methods in recent years. However, it has been recognized that there is not enough data available to estimate fire risk and fire safety performance of fire protection measures. In relation to this situation, it is important to discuss about the treatment of the evacuation starting time in the evacuation safety assessment method. And, in fire risk assessment method, it is also recognized that the discussion of treatment of both fire incident rate and performance of public fire departments is important.

On the other hand, as a new movement to be worth attention from the viewpoint of performance-based design and regulation, the Fire and Disaster Management Agency (FDMA) started the 3-year project for developing synthetic fire safety design method in 1999.

Along with the recent current of deregulation of technological standards in the Fire Codes in Japan (Fire Service Law etc.) such as standards for installation of fire protection equipment and the possible movement toward performance-based fire codes in the future. This project aims to develop evaluation methods of performance of fire protection systems such as sprinklers, fire alarm systems, and smoke exhaust systems together with a guideline for performance-based design method and the database of engineering tools and knowledge.

In the current studies regarding fire risk assessment method, most of them aim at proposing a kind of framework of fire risk assessment, because of lack of available data. Therefore, it is necessary to collect more data that is useful to fire risk assessment, and also to grope for the method to put the current data to practical use.

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A RESEARCH PROGRAM TO DETERMINE WHEN AND HOW TO INCLUDE SUBLETHAL EFFECTS OF SMOKE IN FIRE SAFETY DECISIONS

Richard G. Gann
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8650

ABSTRACT

It has long been realized that the sublethal effects of smoke can affect survival in fires, but only sparse data were available on which to base fire safety decisions. A recent draft standard under consideration in the International Standards Organization Committee on Fire Safety has prompted an industry/government consortium to conduct research on the role of sublethal effects of smoke in evaluating building and/or product fire safety. This paper outlines the components of this high visibility and high potential impact study.

BACKGROUND

Smoke from all fires presents a potential for harm, and smoke inhalation is the largest single factor in fire fatalities. The danger from smoke is a function of:

- the toxic potency of the smoke (often expressed as an EC_{50}, the concentration needed to cause the effect on half of the exposed population) and
- the integrated *exposure* a person experiences to the (changing) smoke concentration and/or thermal stress over some time interval: $\int C(t)\,dt$.

Some of the effects of smoke increase with continued exposure, others occur instantaneously. A person's survival depends on such factors as the exposure, the type of effect, the person's will to escape the fire, intervention by others, etc. Unfortunately, the only representative real-world data we have on smoke effects in real fires are for death or hospitalization that occurs proximate to the fire event.

Past studies have shown that about 3/4 of all U.S. fire deaths are due to inhalation of smoke[1]. About 2/3 of these occur outside the room of fire origin from fires that have proceeded beyond the room of fire origin. Fire modeling shows that it is difficult to produce lethal levels of smoke within the room of fire origin and that heat is the first threat for all but extremely toxic smoke (Figure 1).

Not all countries will have the same profile of fire deaths as in the U.S. For example, in the United Kingdom, where the national fire statistics are comparable in quality to those in the U.S., the experience appears to be quite different. Most people die within the room of fire origin, still from smoke inhalation. This suggests that smoldering fires, with the person in close proximity to the combustion, are relatively more prevalent there.

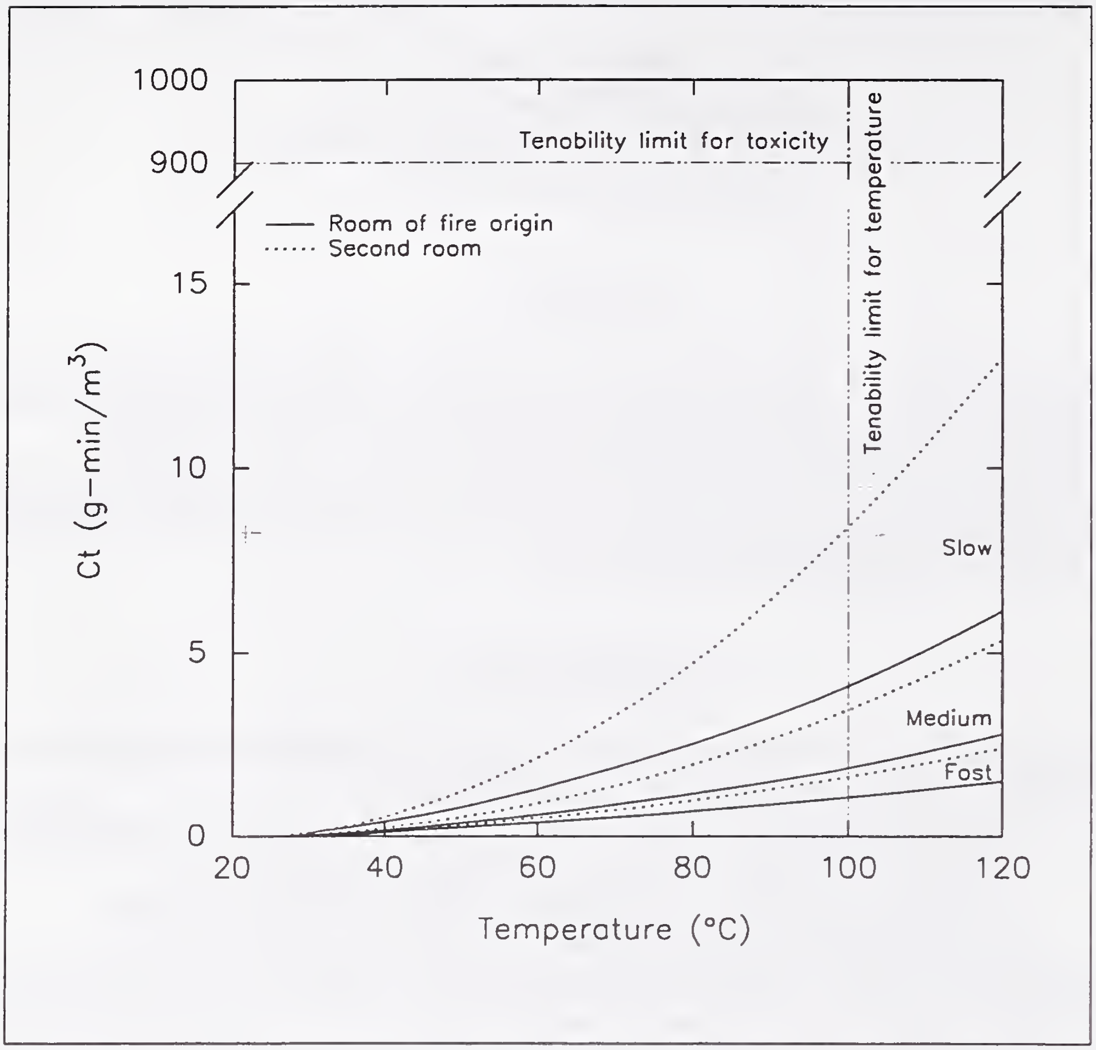

Figure 1. Relative Impact of Toxic and Thermal Effects in the Room of Fire Origin and a Second, Connected Room for a Range of Fire Growths

SMOKE LETHALITY

At the dawn of modern fire research in the 1970s, numerous lab-scale apparatus were developed for measuring the lethality of combustion smoke [2]. Examples include the NBS cup furnace, the DIN (German) tube furnace, and the UPITT method (adopted by New York State). None of these reflected relevant fire conditions and none were tested against real-scale fire tests to determine the accuracy of the smoke they produced.

In the late 1980s, a lab-scale test method for smoke lethality was developed at NIST, based on an apparatus developed at the Southwest Research Institute [3]. The method exposes a product specimen to fire-like radiant energy. An algebraic equation (the N-gas Equation) is used to predict lethal toxic potency from the concentrations of a small number of gases (CO, CO_2, HCN, HCl, HBr, reduced oxygen) that are emitted during the combustion. This equation is based on data from exposure of rats to these gases, individually and in combination. [The CO data have been linked to lethal human exposures.] The prediction is then verified by repeat experiments using the same apparatus, now exposing rats to the smoke. The results from this apparatus have been verified against animal tests of the smoke from post-flashover room fires of wood, PVC, and a rigid urethane foam [4]. For post-flashover fires, the N-Gas Equation is corrected for the high CO resulting from underventilation in the fire room. The accuracy level is adequate for use in hazard analysis. This method has been adopted as NFPA 269 and ASTM E1678.

SUBLETHAL EFFECTS OF SMOKE

There are a wide range of impacts that smoke can have on people, short of causing death during their exposure:

- physical collapse (incapacitation)
- reduced egress speed due to, *e.g.*:
    - sensory (eye, lung) irritation
    - visual obscuration
    - heat or radiation injury
- reduced motor capability
- decreased mental acuity

Each can limit the ability to escape, to survive, and to continue in good health after the fire.

Comparison of data from bench-scale incapacitation and lethality experiments indicates that the former results from exposures one-third to one-half those that cause death [5]. There is a paucity of data on other sublethal effects, and no such ratios with lethality have been derived for them. It is presumed that the exposure ratios that will cause the more subtle effects, such as a decrease in mental acuity, will be smaller than the incapacitation ratio.

ISO DIS 13571

This draft international standard (DIS) was prepared in subcommittee SC3 on Toxic Hazards in Fire (now Fire Threat to People and the Environment) of the ISO TC92 Committee on Fire Safety. It provides generic equations for assessing smoke hazards - inhalation of narcotic gases, exposure to irritant gases, visual obscuration, and heat. DIS 13571 formalizes the inclusion of sublethal effects, including the variation of the effects of smoke on more susceptible segments of the population.

The balloting on the earlier versions of this document was highly positive. However, there has been an increased awareness of the constraints these concerns impose on product design, resources, and building functionality. An important ballot for this DIS to become an international standard has just been concluded, but at the time of this writing, the results have not been compiled.

There are a variety of shortcomings with DIS 13571.

1. DIS 13571 bounds the smoke effects issue describes above by establishing a "no harm" level based on 1-hour occupational exposures that have been deemed safe. These levels are a factor of 10 below the "serious harm" exposures. Table 1 lists some of these numbers.

TABLE 1. EXPOSURE LIMITS FOR SELECTED GASES

Safe Exposure for All		Potential for Serious Harm
3,500 ppm-min	CO	35,000 ppm-min
100 ppm	HCl	1,000 ppm
3 ppm	acrolein	30 ppm

Simple calculations show that for a room 30 m^3 (1500 ft^3), a 1-minute exposure to the smoke from 50 g of a typical halogenated FR product or from 150 g of smoldering wood would be intolerable. Further, it has been estimated that these CO levels would produce blood carboxyhemoglobin levels lower than those of a moderate smoker.

These results, then, do not make sense. In the U.S., we experience about 2 million reported fires per year, certainly all larger than the above fire sizes. Only about 1 percent of these fires result in reported injury or death. The minimal fires mentioned above are below detectable limits. They should rarely result in harm to people.

Thus, it appears that the suggested "band width" between lethality and safety is too broad. A prime scientific question is: how do we determine this ratio correctly within today's state-of-the-art?

2. The presumption that the effects of irritant fire gases is instantaneous remains to be verified.

3. The equations for the combination of fire gases to produce sublethal effects are generic and have not been validated.

THE FIRE PROTECTION RESEARCH FOUNDATION PROJECT

In light of the potential impact of DIS 13571 on product markets, a number of companies and trade associations have combined to support a project under the NFPA Fire Protection Research Foundation. The objective of the project is to ascertain whether there is a role for the sublethal effects of smoke in evaluating building and/or product fire safety, and if so, then:

- determine the fire scenarios in which the role is substantial,
- develop a protocol for obtaining data on or best estimates for sublethal effects of smoke on people and their ability to escape and survive, and
- develop guidance for policy makers for using these data in fire risk and hazard analysis.

This is a serious public safety and potential product regulation issue that needs to be addressed. The formulation of the project reflects that it is highly unlikely that new data on controlled human exposures will be possible; no human or animal exposure studies are currently planned in this project. However, there is a need for carefully documented, quantitative analysis of the existent data and of the principles for their use, e.g., what is the accuracy of extrapolating from animal tests to human response. There is a current timeliness for these results, as prescriptive codes are being revised and performance-based codes are emerging.

The following are the planned components of the project:

Task 1: Toxicological Data

- Review the existing data on lethal and sublethal physiological effects of heat, smoke, fire gases/aerosols and their combinations on animal species and humans
- Identify the best such data (including from non-fire literature) and determine uncertainty bars
- Review the literature on the relative penetration into the lungs of gases and aerosols of differing dimension
- Review the data on people's susceptibility as a function of age, physical condition, etc.
- Examine the methods for extrapolation of the animal data to people and determine the associated uncertainty levels
- Determine how to obtain more/better data without using human subjects

Task 2: Smoke Transport Data

- Review the literature on the dimensions of aerosols produced in fires
- Review the literature on the losses and agglomeration of gases and aerosols as the smoke moves from the fire
- Review the literature on models of the solubility in and evaporation from aqueous aerosols of toxic gases in the humid fire effluent

Task 3: Behavioral Data

- Review the relationships between physiological effects (especially from irritant gases) and impairment of human escape
- Appraise methods for extrapolating such effects in animals to people and estimate the uncertainty levels
- Determine how to obtain more/better data without using human subjects

Task 4: Fire Data

- Review data from reports on fires, on chemical exposures, from hospitals, etc. to characterize our ability to determine the importance of sublethal exposures on escape, survival, and health
- Estimate the magnitude of the importance (relative to lethality) of sublethal effects, with uncertainty bars
- Identify ways to improve future gathering of case and epidemiological data

Task 5: Risk Calculations

- Based on past fire risk analyses, identify fire scenarios for which significant incidence data exist
- Compile list of primary factors that would mitigate the incidence of fire and accompanying casualties
- Perform calculations to estimate the decreased chance of escape and survival in these fire scenarios when people are exposed to sublethal levels of smoke
- Verify, to the extent possible, with the data from Task 4 or from specific fires where the exposure information can be inferred

Task 6: Fire Characterization

- Determine analytically and/or experimentally the fire types and sizes (e.g., single burning object, spread to successive objects) that can produce atmospheres to which sublethal exposure would result in significant decrease in survival likelihood
- Develop accurate reduced-scale measurement methodology for obtaining smoke (component) yield data for commercial products

Task 7: Societal Analysis

- Develop a method and case studies for projecting the enhancements of public safety and the costs to society that would accrue from the inclusion of exposure to sublethal levels of smoke in design specifications

Task 8: Dissemination

- Compile a reference document for the subject
- Archive the research findings

- Prepare practical guidance sheets for decision makers
  - based on the existing literature and the Project outcome
  - delineating the relative importance of lethal and varying levels of debilitating smoke exposures

Project Output

- Identification of fire scenarios for which sublethal smoke exposures would reduce survival significantly
- Compilation of best knowledge of effects on people of sublethal exposures to fire smoke
- Validated method for obtaining product smoke data for inclusion in appropriate fire hazard and risk analyses
- Benefit/cost analysis of including consideration of exposure to sublethal levels of smoke in design specifications

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Fire Safety Design and Fire Risk Analysis Incorporating Staff Response in Consideration of Fire Progress Stage

Yoshiro Yashiro[*] , Manabu Ebihara[**] , Hiroaki Notake[**]
* Institute of Technology, SHIMIZU Corporation, 3 Echujima Koto-ku Tokyo, JAPAN
** OHSAKI Research Institute, 2-2-2 Uchisaiwaicho Chiyoda-ku Tokyo, JAPAN

Abstract

The purpose of this study is to propose a framework for fire risk analysis. The method used involves modeling the fire escalation process into fire phases and evaluating the fire risk from the probability of fire phase escalation. The particular feature of this risk analysis method is that it also takes into account the actions of security staffs in the event of a fire, and the reliability of fire protection measures, both of which greatly affect the degree of damage that may result from a fire. This evaluation method may also be used in fire safety design as a systematization method of fire protection measures against a target fire phase of the building in question.

1. Introduction

Generally, the success or failure of fire protection measures and the action taken in the event of a fire can be expected to have a major effect on the spread of a building fire. However, in the conventional deterministic evaluation model of fire safety, these factors are not considered. Such considerations are usually treated in only a qualitative manner during the process of fire safety design. In the large and complex buildings in recent years, the response of fire safety personnel (security staff) in an emergency is a factor of major significance to fire safety.

The purpose of this study is to formulate a fire safety assessment method that takes into account the action of security staff in the event of a fire and also the reliability of major fire protection measures. For this purpose, we treat the spread of fire as an escalation of the fire thorough various stages (known as fire phases). The method assesses whether or not measures to prevent escalation at each fire phase can be brought into effect within a critical time of the phase being reached. In doing this, probability data of the starting time of security staff action are used. Then, fire safety is evaluated from the probability of escalation from each fire phase to the next. In this report, we propose a framework for risk analysis that incorporates security staff response based on the fire phase concept. We then look at the features of this analysis method from the perspective of fire safety design.

In addition, this fire phase-based method of risk analysis was developed as a part of the research project being carried out by Tokyo Fire Department. [1) 2)]

2. Classification of Fire Phase

Seen from the perspective of the aims of fire safety, it is useful to express the fire spread in terms of various stages. This is because the fire protection measures can be planned and organized systematically against the specific conditions that cause to escalate from a certain stage to the next. This understanding can clarify the target of fire safety design and provide alternative of fire safety measures. In this study, we define a fire as a process of escalation through various phases from the viewpoint of fire safety design.

Using this approach, the threshold of the initial stages is set from the capable condition for staff response and the performance of fire protection measures. The critical time for security staff is defined according to the condition of hindrances against human action, so that smoke layer height is adopted as the threshold. Once a room fire escalates, it spreads in units of space, such as by room, compartment, and floor. We can understand the phases as the level of fire damage. Figure 1 illustrates the defined fire phases and the thresholds for phase escalation.

It is important to remember that, depending on the particular characteristics and the success/failure of fire protection measures, fire does not always progress in order through these phases, but may skip phases.

The conditions for escalation of fire phase are analyzed using fault tree analysis, and the failure modes of these are composed fire protection measures and staff response. The fire spreading process is

only considered at the point of escalation between fire phases. This makes it easier to incorporate fire safety response to a fire and the reliability of fire protection measures into the evaluation of fire safety. In this process, the dynamic aspects of fire spread are taken into account in evaluating the critical time of each fire phase.

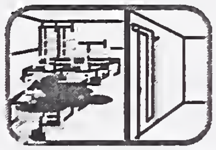
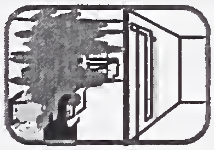
Fire Phase	Image of Fire Phase	State of Period of Fire Phase	Threshold of Fire Phase Escalation	Combination of Fire Prevention Actions
Phase I	 Fire Room Adjacent Room	Fire occurs and is growing up. It is able to be extingished by fire security staffs.	Min.(T_{950} T_{Ph2}) T_{950}: Heat Release Ratio Reaches 950kW	Cntrol automatic Detection System Emergency Elevator Fire Extinguisher Standpipe System Sprinkler System
Phase II	 Fire Room Adjacent Room	Fire is growing and is not able to be extiguished by fire extiguisher. Heat smoke layer forms under the ceiling of the fire room.	T_{Ph2} Limitation of the Critical Egress Time of Fire Room Smoke Layer Height < Human Height	Standpipe System Sprinkler System
Phase III	 Fire Room Adjacent Room	Fire is growing and people cannot stay in the fire room. Temperture of the fire room is growing up.	T_{Ph3} Temperture of Smoke Layer of Fire Room Reaches 600 • • (incombustible) 300 • • (combustible) •@	Closing the doors of the Fire Room Starting Smoke Exhaust System Turning off Air Conditioning System
Phase IV	 Fire Room Adjacent Room	Fire spreads over the fire room (flashover) , and keep buring in the fire room.	T_{Ph4} Fire Resistance Time of Fire Room (door and wall)	Fire Brigade Action Emergency Elevator Vestibule
Phase V	 Fire Room Adjacent Room Corridor Stairs	Fire spreads out to adjacient rooms.	T_{Ph5} Fire Resistance Time of wall or Door of Fire Room	Fire Brigade Action
Phase VI (= phase V)	 Fire Room Adjacent Room Corridor Stairs	Fire spreads to corridors.	T_{Ph6} Fire Resistance Time of Corridor (Compartment)	Fire Brigade Action
Phase VII	 Fire Compartment Corridor Stairs	Fire spreads to lobbies.	T_{Ph7} Fire Resistance Time of Compartment (Vestibule)	Fire Brigade Action
Phase VIII	 Fire Compartment Corridor Stairs	Fire spreads to upstairs.	T_{Ph8} Radiant Heat of Flame Flame Height Reach to Upper Floor	Fire Brigade Action

Figure 1: Fire Phase and Threshold Classified from the Perspective of Fire Safety Design [2) 3) 4)]

3. Framework of Fire Phase Escalation

3.1□ The concept of fire phase escalation assessment

Figure 2 outlines the concept of the assessment of fire phase escalation. The starting time of proper action and the critical time of each fire phase are compared in the respective fire phases. If the required response for a certain fire phase is not carried out within the critical time, the fire phase will progress further, whereas if the response is carried out in time, further escalation will be successfully prevented. Further, the critical time in each fire phase depends on fire protection measures and sequence of fire phase escalation.

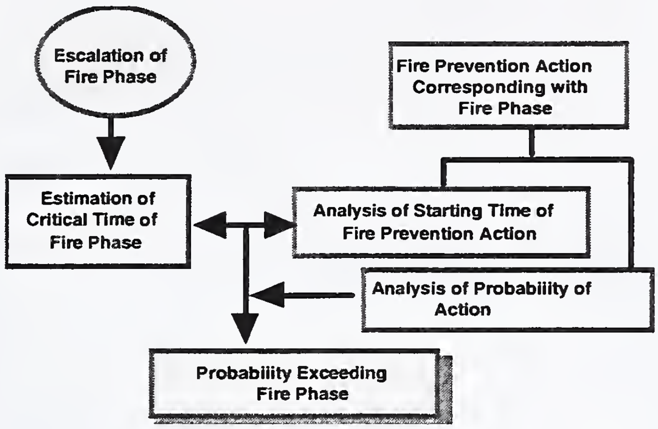


Figure 2: Framework of Assessment of Fire Phase Escalation

3.2 Calculation of Critical Time

The critical times of fire phases are calculated using analytical methods under the condition of the success or failure of fire protection measures in a deterministic way. Further, after the outbreak of a room fire, the fire resistant performance of the compartment is taken as an index of the critical time for a case where the doors are closed. Therefore, if the fire duration time is greater than the fire-resistant time of the doors or walls, the resistant time of the doors/walls is the critical time of the phase. If all doors of a compartment are not closed, the fire will spread immediately to the next compartment. Figure 3 illustrates the analytical models of fire and smoke behavior used. We adopted the BRI models.

3.3□ Evaluation Procedure

In evaluating fire phase escalation, we can calculate the exceeding probability index of escalation of a certain fire phase by using the probability of the starting times of staff response in that phase and the probability of occurrence of that phase. This procedure is repeated for each phase. Evaluation of overall risk is carried out using expected value of burnt area, and we can obtain a full understanding of the characteristics of fire safety performance via risk curve represented in the form of the exceeding probability of each fire phase. The probability density functions are applied to analyze the data of the fire safety response action, and the reliability of fire protection measures is used in the condition for calculating the critical time of each phase.

Figure 4 illustrates the relationship between the time at which fire safety action is taken and the starting time at which the design fire model begins. We assume a smoldering stage here. The time elapsed after the fire outbreaks until the automatic fire detection system triggers is assumed to be 60 seconds, and this is the point at which the fire model starting. This time of difference depends on the type of fire detection system.

4.□ Starting Time of Staff Response in the Event of Fire

To determine the staring time of fire safety actions in the event of a fire, we investigated the training of fire safety center personnel. The Tokyo Fire Department conducts the training courses for such staffs. The training program includes the use of a fully equipped simulator incorporating a fire control center room

with fire control console, an emergency elevator, an emergency communication equipment, a standpipe, an emergency public-address system, etc. During the training, the times at which different fire safety actions began after the outbreak of a fire were automatically recorded. Six people for a standard team and a fire room on the 22nd floor were assumed,

Fire Phase	Expression of Critical Time for Fire Phase
Phase I	$Min(T_{950}, T_{Ph2})$ $T_{950} = \sqrt{\frac{950}{\alpha}} + T_{lag}$
Phase II	$T_{Ph2} = \left\{ \frac{5}{2} \frac{\rho}{k} \frac{A_{room}}{\alpha^{1/3}} \left(\frac{1}{(1.6 + 0.1 H_{room})^{2/3}} - \frac{1}{H_{room}^{2/3}} \right) \right\}^{3/5} + T_{lag}$
Phase III	$T_{Ph3} = \begin{cases} 600 & (\text{interior finish is incombustible}) \\ 300 & (\text{interior finish is combustible}) \end{cases}$ $T_{Ph3} = 0.0236 Q^{2/3} (h_k A_T A\sqrt{H})^{-1/3} T_{\infty} + T_0 + T_{lag}$
Phase IV • VII	Fire Resistance Time of Compartment
Phase VIII	$\Delta T > 350$ $\int_0^{t} \dot{q}'' dt > 2.0 \times 10^{3}$

Figure 3: Calculation of Critical Time of Fire Phase Escalation for this Study [6]

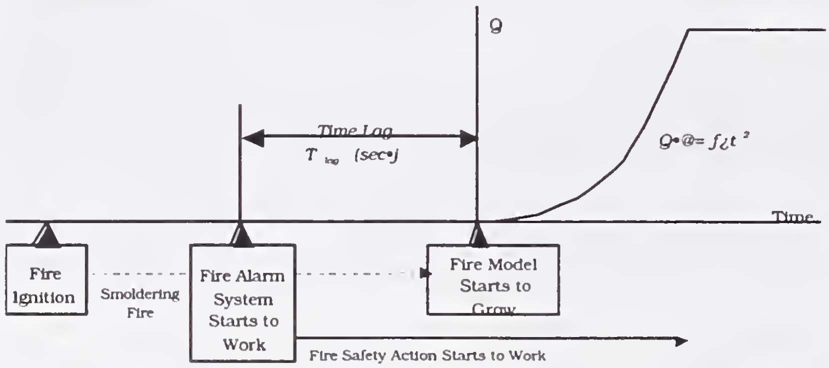


Figure 4: Arrangement between the Times of Fire model and Fire Safety [1) 2)]

and 73 teams were recorded. Three members of staff were dispatched to the fire room and the others took control of the systems in the fire control center after the fire alarm working.

Table 1 summaries these starting times of fire safety actions. Figure 5 - 11 give the distribution of the data. Table 2 shows the reliabilities of the fire safety measures applied in this study. The first step actions after the automatic fire detection system is triggered are control of console and immediate dispatch of personnel to the fire room via the emergency elevator. These personnel then, confirm the existence of the fire, communicating with the fire control center. The standard procedure thereafter is to fight against the fire using fire extinguishers and to close the doors of the fire room. Once confirmation is received by the fire control center, the fire department is contacted. In a large proportion of cases, these initial steps are successful, and there is little difference in the starting times of different teams.

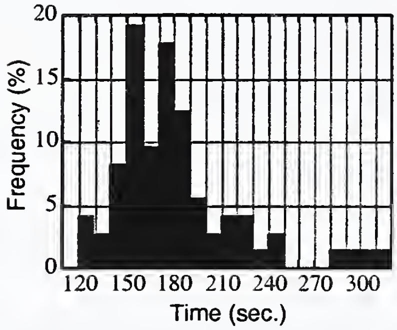
Table 1: Summary of the Starting Times of Fire safety Actions [1) 2)]

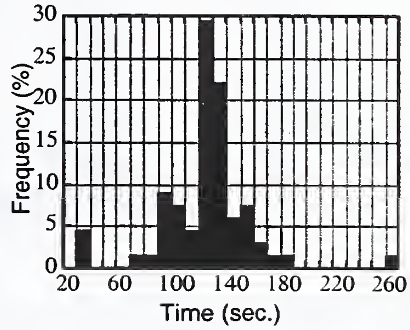
Action	ƒÊ (sec)	ƒÐ (sec)	p (%)	Estimation Curve Type
E0.·E1	120.5	19.8	93.2	Log-Logistic
E0.·E2	189.4	28.0	82.2	Lognormal
E0.·E3	57.2	4.2	98.6	Log-Logistic
E0.·E4	116.0	84.5	87.7	Weibull
E0.·E5	179.1	102.7	80.8	Weibull
E0.·E6	138.6	78.2	100.0	Lognormal

Index	Meaning	Index	Meaning
E0	Arrival at Fire Floor	E5	Turning off Air Conditioning System
E1	Use of Fire Extinguisher	E6	Fire Department Notification
E2	Use of Fire Hose Station	ƒÊ	Average of Starting Time
E3	Fire Door Closing for Compartment	ƒÐ	Standard Deviation of Starting Time
E4	Starting Smoke Exhaust System	ƒ‡	Probability of Action

Table 2: Reliability of Fire Safety Measures Established [2)]

Fire protection measure		Reliability	Reference
Automatic sprinkler system		0.972	Fire data of Tokyo Fire Department (1987-1996)
Automatic fire detection system		0.945	same as above
Fire extinguisher		0.996	same as above
Standpipe system		0.971	same as above
Smoke extraction system		0.974	Annual Inspection Data (1989-1997)
Emergency generating system		0.998	Investigation by Kakegawa [7)]
Fire door	Automatically closing	0.97	Established by Tokyo Fire Department based on investigations
	With inter-locking device	0.91	same as above
Fire shutter		0.91	same as above





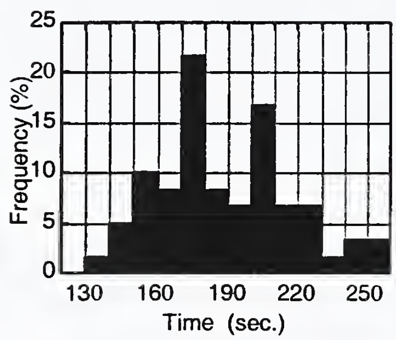
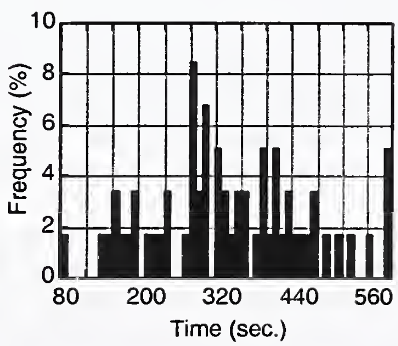
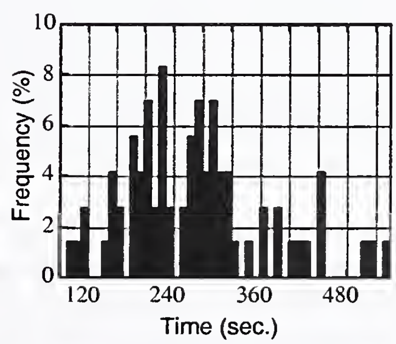


Figure 5. Arrival Time at Fire Floor Figure 6. Time of Fire Extinguisher Usage Figure 7. Time of Standpipe System Usage





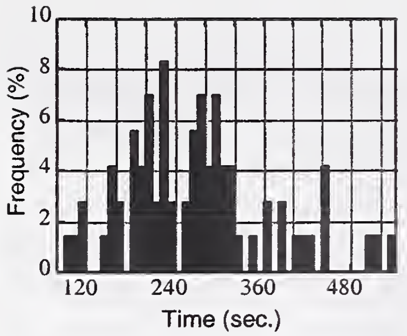
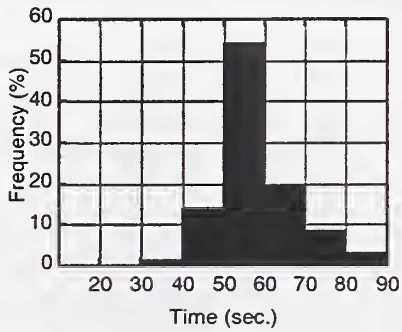


Figure8. Start Time of Smoke Exhaust System after Arrival Time

Figure9. Time of Turning off Air Conditioning System after Fire Detection

Figure10 Time of Fire Department Notification after Fire Detection



□ Figure 11: Time of Closing Door of Fire Room after Arrival Time

Subsequent actions include using the standpipe, using the emergency public-address system, operating the smoke extraction system, and stopping the air conditioning system, etc.□ However, the ratio of implementation of response in these steps begins to fall off, and there is considerable difference among teams. The ratio of standpipe use is 82%, and that for operating the smoke extraction system is 88%. There is large divergence in ratios of different teams. (Note: the emergency public-address system is used in 93% of cases, and also its use usually late.)

5.□ Case Study

As a case study, we applied the new evaluation method to the building shown in Figure 12. Based on the data mentioned above, the time taken for the fire department to arrive at the fire floor was calculated. As a result, the exceeding probability of each fire phase is shown in Figure 13.

In cases where the sprinkler system is not installed, or where the sprinkler system fails (assumed to be a probability of 0.03), the followings can be understood (the case of improved fire prevention systems without SP). The exceeding probability of escalation beyond Phase 2 is 0.4. Because the room is small, the fire grows quickly to the critical condition for staff response, and initial fire extinguishing (phase 2) will not be successful. Then, the probability of the fire reaching Phase 2 is 0.7, and the probability that the fire spread further in the room is 0.4 (that is Phase 3). The probability of fully developed fire in the room the exceeding probability of escalation beyond Phase 3 is 0.15. However, the probability of reaching Phase 5, in which the fire has an impact on the corridor, is 0.03 in exceeding Phase 4, since the probability of closing doors is 0.996.

Equipment that required human intervention tends not to be worked to its full potential. For example, efforts to extinguish fires using standpipe systems are actually quite ineffective. In cases where the smoke exhaust system also requires manual operation, its availability in terms of life safety is limited because it tends to be switched on late. This tendency is particularly notable in the type of building which are comprised of small rooms without fire compartment. A consideration of how this kind of emergency action is actually implemented leads to the conclusion that there is a need to rethink emergency response to match the characteristics of each particular building in question.

Figure 14 illustrates the effectiveness of fire protection measures elucidated from a parametric study of expected value of burnt area in the cases where various fire protection measures are in place or absence. It is clear that sprinkler systems are highly effective. Automatic fire detection systems also have a considerable effect on how much a fire spreads, and implementation of closing door of the fire room also is effective. It is because these lead to success of other fire safety actions in the initial stages. Architectural fire protection measures are not particularly effective in terms of expected value of burnt area, but, from the viewpoint of preventing escalation beyond phase 4, compartmentalizing is highly effective. This parametric study obtains quantitatively the characteristics of the fire safety measures and fire prevention activities.

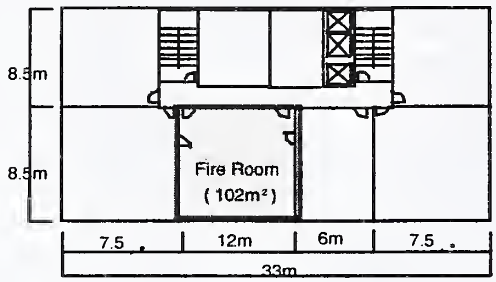


Figure 12: Model Plan of Case study

6. Conclusion

6.1 Effect of Delayed Response

From the analysis carried out here, late response, low implementation ratio of response and wide proportion of distribution of the response time cause to serious fire spreading. In particular, the times of using the extinguisher and the standpipe system and operating smoke control system are found to be late in cases where a fire spreads from a small fire room.

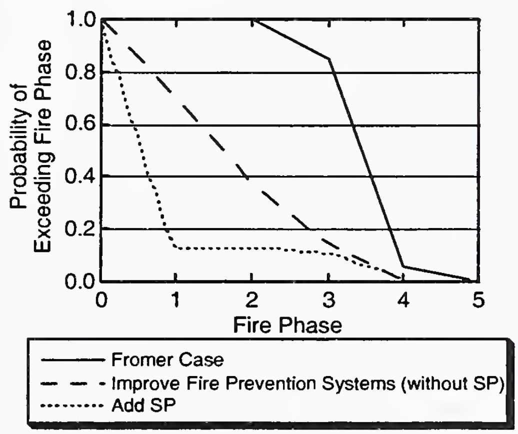


Figure 13: Risk Curve expressed as Exceeding Probability of Each Fire Phase [2)]

Case	N	I1	I2	I3	I4	I5	I6	EFDA •i†F•j	Reduction Rate (0 20 40 60 80 100 (%))
1	0							94.3	•
2	1					•,		94.1	0.1%
3	1				•,			91.6	2.8%
4	1	•,						87.9	6.7%
5	1			•,				85.3	9.5%
6	2	•,			•,			85.3	9.5%
7	2			•,	•,			81.4	13.6%
8	2	•,		•,				79.6	15.6%
9	3	•,		•,	•,			75.7	19.7%
10	1		•,					69.2	26.6%
11	2	•,	•,					63.4	32.8%
12	2		•,		•,			62.4	33.8%
13	3	•,	•,		•,			56.7	39.8%
14	2		•,	•,				42.3	55.1%
15	3	•,	•,	•,				38.3	59.4%
16	3		•,	•,	•,			34.6	63.3%
17	4	•,	•,	•,	•,			30.8	67.3%
18	5	•,	•,	•,	•,	•,		16.7	82.3%
19	1						•,	12.0	87.3%
20	6	•,	•,	•,	•,	•,	•,	0.8	99.1%

Explanatory Notes: N: Number of items Improved

I1: Improvement of Compartmentalization (Fire Resistance Time, Fire Door Closing)

I2: Improvement of Security Staffs' Skill

I3: Improvement of Fire Alarm System

I4: Improvement of Maintenance grade

I5: Addition of Smoke Exhaust System

I6: Addition of Sprinkler System

EFDA: Expected Value of Average Fire Damage Area

Figure 14: A Parametric Study for Response of Fire Protection Measures [2)]

These data reflect the training of fire control center personnel. These indicate the need to maintain the capability to take the correct action. Further, in most cases, a fire control center has between three and six personnel on duty. The smaller this numbers the greater the wide distribution of response time. We believe that this has a very serious impact on the life safety of evacuation except evacuation from fire room.

Generally, when evaluating fire safety performance, design fire scenarios are rarely set such as failure or delayed time of fire safety action. The results of the case study demonstrate that it is necessary to consider suitable response and their sequence for each fire phase. Also, it is important to carry out an overall assessment of automatic fire detection systems, extinguishing systems and building fire protection measures to the target of fire safety design. We believe that phasing and modeling a fire into fire progress stages from the viewpoint of preventing fire escalation is a valuable tool in the systematization of fire protection measures.

6.2 Effectiveness of Phase Escalation Concept for Risk Assessment

We believe that by applying the fire phase concept, we have achieved the following results.

By focusing on the escalation of fire progress stages, it becomes easier to incorporate the success or failure of fire protection measures and fire safety response into risk analysis. The fact that the evaluation includes human factors is the most significant feature of this study, though the methodology is still in the prototype stage.

Further, this method allows us quantitatively understand the fire safety characteristics of a building

from expected value of burnt area and exceeding probability of each phase. Thus, it is possible to plan more effective fire protection measures that meet the needs and characteristics of a particular building. The technique can also be applied to assess the fire response sequence and the number of security staff required.

7. Issues Facing Systematization of Fire Safety Design

This study is simply a prototype risk analysis incorporated security staff response, so there remain the following issues facing progress development.

(1) Determination of initial lag time

In this study, we assume that there is a lag after ignition until the starting time of the fire model ($Q=kt^2$), and that smoke detector works in smoldering stage. Though this lag time depends on the type of automatic fire detection system in use and other factors, it significantly affects the success or failure of the response in the preliminary stage. It is necessary to determine these lag times through experiment or analysis of actual fire data.

(2) Setting of parameters

We have obtained some experimental data of fire safety response, but there is a need for more data to improve reliability. Further, parameters must be set so as to ensure that the data conform to actual conditions (e.g., the degree of experience of security staff, the number of security staff, etc.)

(4) Independence of fire escalation factors

This trial model of risk analysis computes probability of each fire protection measure independently. This independence of factors should be studied further, taking into account the response in the event of a fire, because there are interactions among human factors, fire stages and availability of fire protection measure.

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Reliability Analysis of Standpipe and Foam Extinguishing System based on Annual Inspection Data, Summaries of Technical Papers of Annual Meeting,No.3045, Architectural Institute of Japan, 1998.9

Development of Seismic-induced Fire Risk Assessment Method for a Building

Ai Sekizawa
National Research Institute of Fire and Disaster
3-14-1, Nakahara, Mitaka, Tokyo 181-8633, Japan

Manabu Ebihara and Hiroaki Notake
Izumi Research Institute, Shimizu Corporation
2-2-2 Uchisaiwai-cho Chiyoda-ku Tokyo 100-0011, Japan

Abstract

This study addresses the issue that fire risk would be different from usual at an earthquake, because fire protection systems could be functionally no use even when a building itself has no problem in terms of structural damage. We are developing the seismic-induced fire risk assessment method to evaluate fire risk according to the conditions such as size and type of buildings, installed fire protection systems, and the intensity of input earthquake motion. This paper describes the outline of the framework and examples of results from case study applying a tentative simplified model.

1. Introduction

As of today, while a number of studies have been conducted on fire risk assessment for usual fires, there have been very few on fire risk assessment of a building to post-earthquake fires. For one reason, the concern on fire problems at earthquakes has mainly focused on fire risks on a city area level such as number of fire ignitions and large-scale urban fires, so fire risk on a level of one building has been rarely discussed. However, at the Hanshin-Awaji earthquake, not a few fires occurred from fire-resistive buildings as well as from general wooden buildings. Also, various surveys have revealed that many fire protection systems such as sprinkler systems were damaged by earthquakes and lost its proper function because of mechanical failure and/or deformation by the earthquake motion, though otherwise they should have functioned [1,2,3].

This study focuses on the issue that fire risk would be different from usual at an earthquake, because fire protection systems could be functionally no use even when a building itself has no problem in terms of structural damage. Therefore, it is very significant to develop seismic-induced fire risk assessment method in consideration of these possible difficulties, and to enable to evaluate fire risk according to respective conditions such as size and type of buildings, installed fire protection systems as well as intensity of input earthquake motion. Furthermore, seismic-induced fire risk assessment method would be useful not only to evaluate present risks, but also to estimate how much the risk changes when fire protection systems are improved to be seismic-proof, and to find out effective countermeasures to reduce the risk. The purpose of this study is to develop the framework for seismic-induced fire risk assessment method for a building. As the study is in the middle of the development, this paper describes the outline of the framework and examples of results from a case study applying a tentative simplified model.

2. Damages to Fire Protection Systems and Fires in Past Earthquakes

Even before the 1995 Kobe earthquake, the Marine and Fire Insurance Association of Japan already recognized vulnerability of installed fire protection systems at an earthquake. And, they conducted the investigation study on the reliability of installed fire protection systems especially targeting at sprinkler systems based on the experiences in several past earthquakes including some earthquakes in the U.S. From the results of their investigations[1], it is reported that the percentages of damaged sprinkler systems among surveyed buildings were 34% in the 1993 Kushiro-oki earthquake and 41% in the 1994 Sanriku-harukaoki earthquake where the seismic intensity of both earthquakes were level 6 in JMA (Japan Meteorological Agency) scale that is about 250 cm/sec^2 to 400 cm/sec^2 in ground surface acceleration.

Also, Table 1 and Table 2 show the data on percentages of damaged fire protection systems by type in Kobe City and Osaka City respectively in the Kobe earthquake[2,3]. The seismic intensity in JMA scale was level 6 or level 7 (400 cm/sec^2 or more) in Kobe and was level 4 (25 cm/sec^2 to 80 cm/sec^2) in Osaka. The percentage of damaged sprinkler system in Kobe City is 40.8% and that of fire doors is 30.7%. And, it is more noteworthy that the percentage of damaged sprinkler system in Osaka City is 5.3%, if we consider the fact that the seismic intensity, level 4 in Osaka is much lower than level 6 or 7 in Kobe City. This means sprinkler systems are very vulnerable to seismic motion even though buildings have almost no structural damage.

Table 1 Damages to Fire Protection Systems in Kobe City.

*From the investigation report[2] on the 1995 Kobe earthquake by Kobe City Fire Department.

Type of Fire Protection Systems	Number of Damaged systems	Number of Systems Surveyed	Percentage (%) of Damaged systems
Sprinkler System	222	544	40.8
Indoor Fire Hydrant	107	451	23.7
Foam Extinguishing System	20	83	24.1
Halogenated Extinguishing System	17	162	10.5
Automatic Fire Alarm System	109	542	20.1
Emergency Generator Unit	71	444	16.0
Fire Doors	161	524	30.7

Table 2 Damages to Fire Protection Systems in Osaka City.

*From the investigation report[3] on the 1995 Kobe earthquake by Osaka City Fire Department.

Type of Fire Protection Systems	Number of Damaged systems	Number of Systems Surveyed	Percentage (%) of Damaged systems
Sprinkler System	20	380	5.26
Indoor Fire Hydrant	12	1862	0.64
Foam Extinguishing System	4	117	3.42
Halogenated Extinguishing System	2	301	0.66
Automatic Fire Alarm System	3	6528	0.05
Smoke Exhaust System	3	31	9.68
Stand Pipe	11	2144	0.51

In the 1995 Kobe earthquake, there were 261 post-earthquake structure fires, 83 (31.8%) out of which started from fire resistive buildings and 76 fires (29.1%) occurred from the buildings which height were 4 floors or more. There were four fires from the buildings installed with sprinkler system as shown in Table 3. As for three of these four fires, sprinkler system was not used. Among the above three fires, two fires that occurred at midnight spread beyond a place of fire origin, resulting in the burned area 3,600 m^2 and 35 m^2, but the other one fire was fortunately suppressed in the early stage by occupants with fire extinguisher. Therefore, if fires occur when occupants are absent and sprinkler system loses its function, fires may not be controlled and would cause large fire loss.

Table 3 Outline of Fires from the Buildings Installed with Sprinkler System in the 1995 Kobe Earthquake.

No.	Name of City	Time of Ignition	Features of Building			Usage of Sprinkler System	Burned Area (m^2)	Fire Suppression Action in the Early Stage by Occupants
			Height # of floors	Floor of Fire Origin	Occupancy			
1	Suita	17th, 06:15	11F	8F	Laboratory	Used	0	Success by Fire Extinguisher
2	Kobe	19th, 01:20	2F	1F	Warehouse	Not used	3,600	No Action and Fail
3	Kobe	18th, 02:20	11F	3F	Office	Not used	35	No Action and Fail
4	Itami	17th, 05:48	8F	7F	Office	Not used	0	Success by Fire Extinguisher

3. Framework of Seismic-induced Fire Risk Assessment Method

The damage level of active and passive fire protection systems in a building is predictable by earthquake response of a building, which is determined by frequency characteristics of earthquake motion input to a building and the vibration property of a building itself. Therefore, if the size and type of structure of a building in a particular site as well as input earthquake motion are specified as input conditions, the damage level of active and passive fire protection systems can be estimated to a certain extent. In this study, peak ground acceleration is adopted as an index of input earthquake motion level. In addition to the above, we consider the condition of response action by security staff at a fire, which is also affected by the intensity of an earthquake.

To develop a seismic-induced fire risk assessment method, we incorporated the failure probability of active and passive fire protection systems caused by an earthquake, which is main contribution of this study, into the existing fire risk assessment method[4] for usual fires. First, we introduce a simplified model to estimate earthquake response of a building, which is the base for other models or estimation to predict the damage level of active and passive fire protection systems. Then, we construct the functional failure prediction model for sprinkler systems as a representative of active fire protection systems. However, since there is very little data available for constructing prediction models for damage level of elements of compartments such as walls and fire doors, we assume reducing ratio of fire resistance time of compartments based on the data in existing literature at present. Also, we tentatively assume the failure probability of needed response actions according to the intensity of input earthquake motion. After estimation of failure probability of active and passive fire protection systems,

the fire risk assessment method to predict burned area on a given fire scenario is introduced to assess the potential fire risk of a building at an earthquake. The outline of the conceptual framework for the seismic-induced fire risk assessment method is shown in Figure 1.

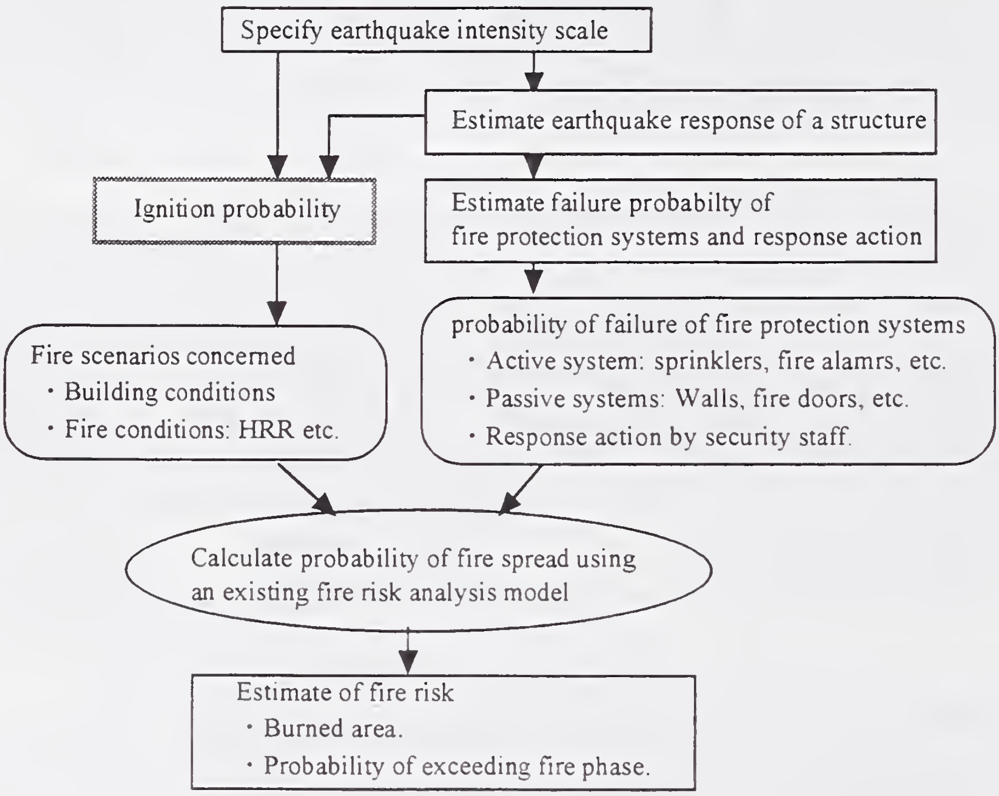

Figure 1 Conceptual Framework of Seismic-induced Fire Risk Assessment Method.

4. Prediction Model of Functional Failure Probability for Sprinkler System

As stated earlier, there could be functional failure on various fire protection systems at an earthquake, and most of those failure are likely to occur in the water suppression systems such as sprinkler system. The water suppression system does not perform its proper function as a whole system if whichever part goes wrong, because every part of these systems is linked with piping network which should keep a certain level of water pressure. In this paper, therefore, we consider the failure probability of sprinkler system as a representative case for active fire protection systems as well as the most dominant element to be addressed.

The prediction model of failure probability of sprinkler system can be constructed based on a sum-set of seismic-induced damage probability on each part of sprinkler systems such as water tank, pump, vertical piping, horizontal piping, and sprinkler heads. For each part, considering the experiences of damages caused by past earthquakes, the dominant modes of functional failure are identified. Then, the probability of damage of each part can be given as a function of intensity of input earthquake motion. Also, the probability of failure as a whole sprinkler system is estimated with a sum-set of the probability of damage of each part. Figure 2 shows the concept mentioned above for sprinkler systems for example.

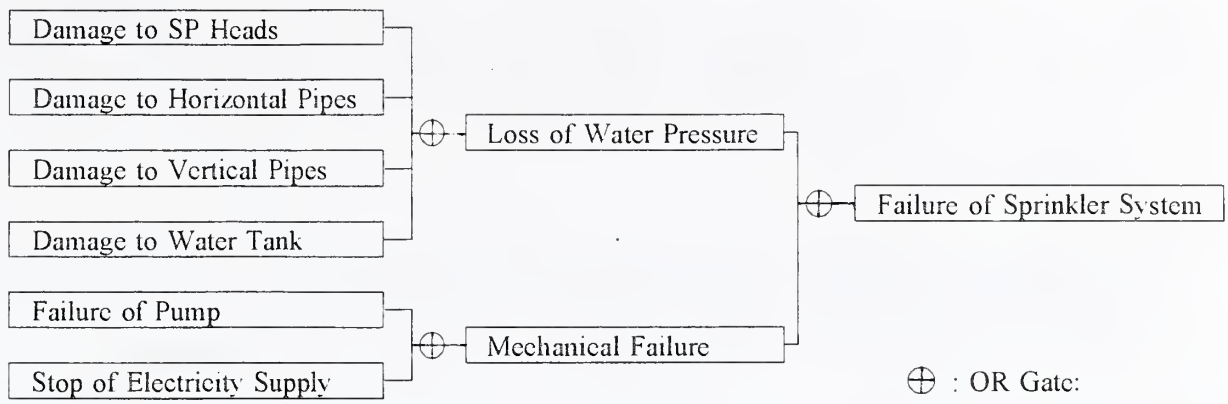

Figure 2 Fault Tree for Failure of Sprinkler System as a Whole.

By the way, even in daily time, there is certain probability of functional failure of fire protection systems caused by maintenance problems. Therefore, the probability of functional failure of sprinkler system at an earthquake is obtained by the product of the failure probability in daily time and the failure probability caused by an earthquake which is estimated as a function of earthquake response velocity. For the part i of sprinkler system, the failure probability at an earthquake is expressed as the following.

$$P_{si}=f_i(v)\cdot P_{di}$$

where,

P_{si}: Probability that part i of sprinkler system does not operate at an earthquake.
$f_i(v)$: Seismic-induced failure function for part i.
v: Earthquake response velocity. (cm/sec)
P_{di}: Failure probability in daily time.

There are two kinds of levels required for seismic-proof design of a building by the Building Codes in Japan. As to the respective levels, a standard value of response velocity as an input of earthquake motion is given for seismic-proof design in 25cm/sec for the grade 1 and 50cm/sec for the grade 2. In consideration of the relation to seismic-proof design of a building, the criteria for dividing the levels of failure probability of sprinkler system is given here using the above values and the seismic-induced failure function $f_i(v)$ for pipes and heads is defined corresponding to response velocity as shown in Table 4. The values of failure probability in this table are assumed based on the data from the investigation report[3] on the Kobe earthquake by Osaka City Fire Department.

Table 4 Failure Probability of Sprinkler System to Earthquake Response Velocity.

Response Velocity : Vr (cm/sec)	Probability of Failure (%)	
	Pipes	Heads
$0 < Vr \leqq 25$	20	20
$25 < Vr \leqq 50$	20	30
$50 < Vr$	30	40

Sprinkler system can not achieve its expected function as a whole system when any part of the system lose the function. Therefore, probability of functional failure of sprinkler system is calculated as the sum-set of failure probability of each part (P_{si}).

$$F_{sp}=1-\prod_{i=1}^{k}(1-P_{si})$$

where,

F_{sp} : Probability of functional failure of sprinkler system as a whole.

k : Number of parts which consist of sprinkler system.

P_{si} : Probability that part i of sprinkler system does not operate at an earthquake.

5. Damage to Fire and Non-Fire Compartments

There are very little data from investigation available for predicting the damage of compartments caused by earthquakes. On the other hand, the assumed criteria on the damage to fire resistance time of compartments according to relative story displacement are described in the design guideline[5] of compartments issued by the Architectural Institute of Japan. Therefore, we put the reducing ratio of fire resistance time of fire and non-fire compartments depending on the relative story displacement after the above criteria as shown in Table 5.

Table 5 Reducing Ratio of Fire Resistance Time to Relative Story Displacement.

Relative Story Displacement : Dr	Reducing Ratio of Fire Resistance Time to Normal Condition	
	Fire Compartments (60min.)	Other compartments (30min.)
$0 < Dr \leqq 1/400$	1.0	1.0
$1/400 < Dr \leqq 1/300$	1.0	0.5
$1/300 < Dr$	0.5	0.0

6. Seismic Impact to Fire Protection Action by Security Staff

Fire protection action by security staff must be affected by earthquake motion, but the analytical estimate of how such response action is impacted according to the seismic intensity has not been done yet. At present, therefore, based on the existing explanatory description of human response condition corresponding to the JMA seismic intensity scale, we put the reducing ratio of execution probability of fire protection action by security staff in usual time depending on response acceleration as shown in Table 6.

Table 6 Reducing Ratio of Probability of Fire Protection Action by Security Staff.

Response Acceleration : Ar (cm/sec^2) $0 < Ar \leqq 100$	Reducing Ratio of Probability of Fire Protection Action to Normal Situation
$100 < Ar \leqq 250$	1.0
$250 < Ar$	0.5
	0.1

7. Case Study

The results of a case study applying the tentative simplified assessment method to a model building are introduced here to see how seismic-induced fire risk changes depending on the intensity of earthquake motion. The conditions and the floor plan of a model building for case study are shown in Table 7 and in Figure 3. And, the parameters on failure probability and reducing ratio of performance of fire protection systems and response action according to peak ground acceleration are shown in Table 8. As an example of results of a case study, Figure 4 shows the change of "Expected Fire Spread Area" (hereafter EFSA: in m^2) as a function of "Peak Ground Acceleration" (hereafter PGA: in cm/sec^2). The increase of EFSA at 100 of PGA is derived only from failure of sprinkler system, but the increase of EFSA from 200 to 400 of PGA is due to both failure of sprinkler system and decreasing probability of fire protection action by security staff. Then, the rapid increase of EFSA from 500 of PGA is derived from additional influence by reduced performance of compartments as well as the above two factors. To compare with EFSA from 500 of PGA, the value of EFSA at 100 of PGA is relatively small. However, if the premise, that fire brigades are expected to arrive the

Table 7 Conditions of Case Study.

Occupancy of Building	Office
Structure Type of Building	Steel Frame
Number of Floors	20 floors
Floor Height	4.0 m
Area of Floor	1,538 m^2
Floor of Fire Origin	5th Floor
Area of Room of Fire Origin	384.4 m^2
Room Height	2.7 m
Fire Growth Rate (α in $Q=\alpha t^2$)	0.05
Density of Fire Load	30 kg/m^2
Soil Type of the Ground	Soil Type -1 (Hard Soil)
Peak Ground Acceleration: Input Earthquake Motion	from 0 (Normal Condition) to 600 (cm/sec^2)

Table 8 Parameters of Failure Probability and Reducing Ratio of Performance of Fire Protection Systems and Fire Protection Action for Case Study.

Peak Ground Acceleration (cm/sec^2)	Fire Protection Systems					Reducing Ratio of Probability of Fire Protection Action
	Probability of Functional Failure of Sprinkler System			Reducing Ratio of Fire Resistance Time		
	Pipes	Heads	F_{sp}	Fire (60min.)* Compartments	Other (30min.)* Compartments	
0	0.0	0.0	0.03	1.0	1.0	1.0
100	0.2	0.2	0.36	1.0	1.0	1.0
200	0.2	0.3	0.44	1.0	1.0	0.5
300	0.2	0.3	0.44	1.0	1.0	0.5
400	0.3	0.4	0.58	1.0	1.0	0.5
500	0.3	0.4	0.58	1.0	0.5	0.1
600	0.3	0.4	0.58	0.5	0.0	0.1

* Fire resistance time here is specified for this case study.

scene normally, is changed to be more unfavorable and/or if a seismic-induced fire occurs at night when security staff are fewer, the profile of EFSA in Figure 4 would be different and the values of EFSA would be probably much larger.

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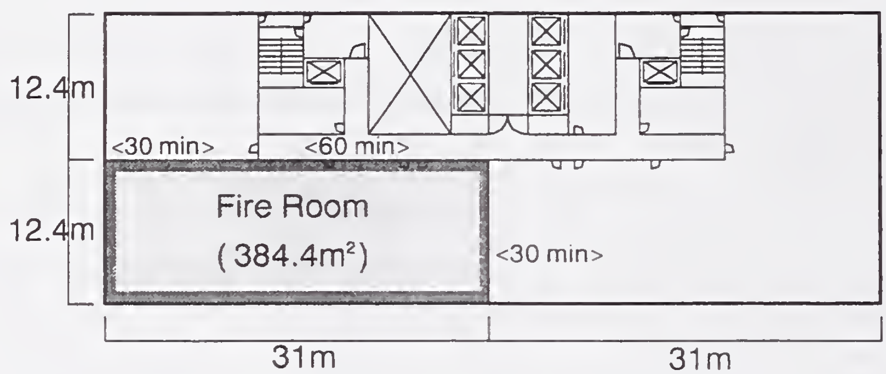

*Fire resistance time of walls and doors is indicated in < >.

Figure 3 Floor Plan of a Building for Case Study.

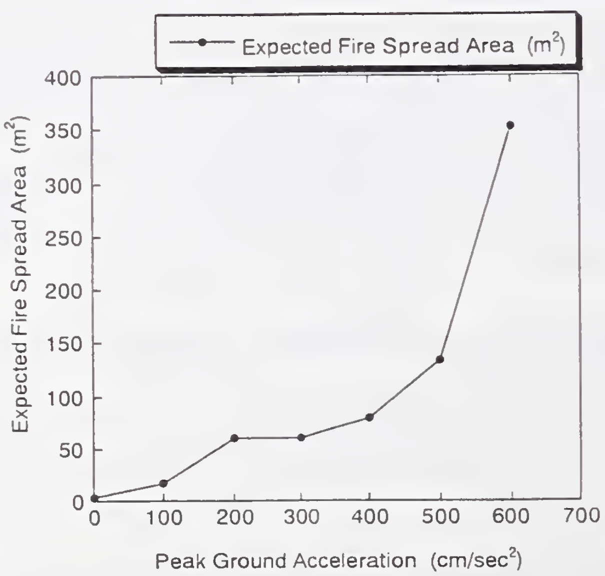

Figure 4 Expected Fire Spread Area as a Function of Peak Ground Acceleration.

NEW DEVELOPMENTS IN EXIT89

Rita F. Fahy
National Fire Protection Association
1 Batterymarch Park
Quincy MA 02269-9101 U.S.A.

ABSTRACT

EXIT89 is an evacuation simulation computer model for high-rise and other large buildings that was first written by the author in 1989. Work on the model has continued since that time, and additional features have been added, including the treatment of contra flows (travel against on-coming traffic or other restrictions) and travel both up and down stairs. These features, as well as those added previously, are crucial to the realistic simulation of the evacuation of large numbers of people in large buildings, where people of differing abilities, with varying reaction times, and with or without staff assistance, may encounter crowds or other path obstructions during their escape.

INTRODUCTION

In 1989, EXIT89 was a fairly simple network model, written in BASIC, that could calculate the shortest routes in a large building with a large number of occupants and move people along those routes using travel velocities based on occupant densities along the paths. The effect of the presence of smoke could be modeled, based on smoke output data from FAST, the fire and smoke movement model then incorporated in HAZARD I, or the user could enter smoke blockages manually. Pre-movement times were treated by setting at each location a delay time which applied to all occupants of that location.

At that time it did not include several essential features necessary to make it more useful in real-life applications, such as the presence of disabled occupants, a more random distribution of pre-movement delay times among occupants, the use of travel paths other than shortest routes, travel up stairs from basement levels, and contra flows. Those features have since been added to the model and will be described below. A brief review of the other options will also be covered.

PRE-MOVEMENT TIME

Even in a planned and announced evacuation exercise, movement will not start instantaneously upon activation of an alarm. For EXIT89, the author chose to give pre-movement time explicit attention in the model but through implicit, highly aggregated parameters, combining activities occupants might engage in, such as investigation, alerting others, packing, etc. Time estimates for these parameters can be set using as much proven theory and empirical data as is available.

The user can set pre-movement delays in two ways. The first is to specify the delay that will occur at each occupied node. In this way, the user is able to model situations where, for

example, the occupants might have a set of assignments to complete before beginning evacuation, such as shutting down process equipment, or locking away documents or securities. It also allows the user to model situations where an alarm system might be inaudible in certain areas of a building, and occupants in those areas would experience a delay in notification of the need to evacuate.

But that still has occupants within a space acting simultaneously, so the user is also able to set, in addition to the delay times for each node, random delays for the occupants throughout a building. To use this option, the user sets the percentage of occupants who will experience these additional delays, and the minimum and maximum delay times. The model then randomly selects the appropriate number of occupants, and selects delay times along a uniform distribution with the specified minimum and maximum values.

ESCAPE ROUTE OPTIONS

The user can choose between two escape route options. The first is to have the model calculate the shortest route from each location to the outside or other designated location of safety. The other is for the user to specify the routes that occupants will follow. In studies of evacuation behavior, occupants are consistently observed to leave by the exits with which they are familiar, rather than the closest, emergency exits, on which the designers probably relied to achieve the required exit capacity.[1] The familiar routes chosen are often those used on a regular basis, for example, the main entrance into a building.

Other studies have shown that exit choice can be strongly influenced by staff actions or occupant training.[2,3,4] In these incidents, occupants were far more likely to use all available exits, and so reduce the time required to evacuate the building. The shortest route option would be the appropriate choice if the user were confident that occupants could be expected to use, or would be directed by staff to use, the exit closest to their location. If spaces on that floor become blocked by smoke, the model recalculates the network on that floor, assuming that at that point, people would begin to explore their options and would be more likely to find the shortest route.

CALCULATING WALKING SPEEDS

Walking speeds in EXIT89 are calculated as a function of density based on formulas from Predtechenskii and Milinskii.[5] Density is used to calculate the velocity for a stream of people, and people in that stream move at that walking speed. Their formula for the density of a flow or stream of people, D, is:

$$D = Nf/wL \quad (m^2/m^2)$$

where

N = number of people in the stream
f = the area of horizontal projection of a person
w = width of the stream
L = length of the stream

Their model established a maximum density of 0.92 and developed the following equation for the mean value of velocity for horizontal paths:

$$V = 112D^4 - 380D^3 + 434D^2 - 217D + 57 \quad \text{(m/min)} \qquad \text{for } 0 < D \quad 0.92$$

Other formulas were derived for travel on stairs. Adjustment factors were also derived for travel velocities under emergency situations. The body size data used by Predtechenskii and Milinskii was obtained from Russian subjects. Since different body sizes were calculated for Austrian and American subjects, the choice of body size was added to EXIT89's input.[6,7] The user can also select between normal and emergency walking speeds.

HANDLING THE PRESENCE OF DISABLED PEOPLE

Any evacuation model used to evaluate an engineered design must be able to realistically handle disabled occupants, regardless of the size of the building. The author modified EXIT89 so that that the user, when describing the number of occupants at each node, can specify how many of them will travel at reduced speeds. Then for each disabled occupant, the user enters a percentage of the calculated speed at which each disabled person will move. A different value can be entered for each person. Any able-bodied person slowed while assisting a mobility-impaired occupant, including parents with small children, can also be described as traveling at the reduced speed.

This option can also be used to model evacuees who for any other reason will travel at speeds different from others around them. This can include occupants who are unusually fast, by using a speed adjustment factor greater than one.

MODELING THE PRESENCE OF SMOKE

EXIT89 can handle the modelling of smoke effects in two different ways -- by the model reading in output data from CFAST or by the user entering smoke blockages manually. (CFAST is the fire and smoke transport model now used in HAZARD I.)

CFAST calculates and writes to a disk file the optical density of the hot upper layer at each node at each time interval and the height from the floor of the cooler lower layer. With this option, EXIT89 reads this file and determines that notification begins throughout the building when the smoke level reaches that defined for smoke detector activation. Evacuation will begin immediately throughout the building, unless delay times are specified at nodes by the user. Room blockages occur when levels reach that defined for untenable conditions.

Using the second option, the user can input the names of nodes that would become blocked by smoke and the times those blockages would occur. This option was created so that results from other fire and smoke transport models could be used, as well as observations from actual fires in order to do incident reconstructions, rather than having to rely only on

CFAST output. By using this option and not specifying any blockages, the user can model the evacuation of a building with no fire.

NEWEST FEATURES OF EXIT89

Contra Flows: There can be times during an evacuation when the available width of travel for escaping occupants will be reduced by, for example, others traveling in the opposite direction, firefighters or firefighting equipment in stairwells, or other obstructions that have built up along the path.[8,9,10]

EXIT89 calculates travel velocities based on the density of occupants at each location. Contra flows have the effect of narrowing the available floor space for occupants, thereby increasing the density of the crowd in that space and decreasing travel velocity of occupants there.

To model the impact of fire service operations in stairwells, for example, the user can determine, based on predictions of fire department response and incident scene activities, the time(s) at which locations along escape routes will be restricted, as well as the degree to which the locations are restricted. If fire department operations are expected to restrict a stairwell by 50 percent eight minutes after the occupants are first notified of the incident, the user incorporates this estimate by selecting the affected stairwell nodes and inputting the degree of restriction and time of occurrence for those nodes. If nodes later open up again, the same method is used for returning the nodes to their original size.

Data is not currently available on the amount of travel space restricted by contra flows, so since the user directly controls the value used, a range of percentages deemed appropriate by the user can be tested.

Travel *Up* Stairs: The original version of EXIT89 assumed that occupants were escaping from the upper floors of a high-rise building to ground level. In reality, many buildings have significant occupant loads below ground level. Also, in a phased evacuation, only the occupants of the floor of fire origin and the two floors above and below that floor need to be evacuated. Occupants above the floor of origin may be directed to move to a higher floor so that they are not required to pass the fire floor. The model was revised to allow movement *up* stairs.

The following simplifying assumptions have been made:

a) either all occupants will travel on horizontal paths or down stairs, or they will all travel on horizontal paths or up stairs.
b) for buildings with levels above and below grade, the model will be run twice -- once for those above grade and traveling down and once for those below grade and traveling up. Occupants on the grade level should be included in both runs, since their travel will impact, and will be impacted by, the presence of those using the stairs.
c) If the results show that the occupants traveling down will interfere with those traveling up when they all reach ground level or any other common travel path, that

is, if the simulations show that the two groups reach common nodes at the same time, another run should be made using the contra flow feature addressed above, restricting each group's travel path at the appropriate points in time.

The addition of this feature of the model allows its application to a more complete simulation of a complex structure. This includes structures that are built entirely below ground, as well as those that have occupied floors above and below grade level. It also allows the simulation of occupant movement in a building where staged evacuations are planned, where people located on floors immediately above the fire will be moved higher in the building, while those immediately below the fire will move downwards.

VERIFICATION EXERCISES

The final step in the development of a simulation model is to verify its usefulness by comparing its predictions to actual experience. The demonstration of satisfactory predictive capability on a wide range of scenarios should build user confidence in the application of a model in the evaluation of new designs for which data would not be available.

Those features of the model described in this paper were exercised using the results of five actual evacuations in four different buildings, including:

- two evacuation exercises in a hotel, with a subject population that included several disabled adults;[11]
- a staged evacuation exercise on three floors of a high-rise office building;[4]
- a complete evacuation of another high-rise office building, where some occupants traveled up stairways to reach exits;[12] and
- an unannounced evacuation of a department store while occupied by the public.[2]

The case studies were selected because they both were well-documented and allowed the illustration of the important features of EXIT89.

The two hotel evacuations took place in a two-story hotel with a total of 63 guest rooms and 60 test subjects, including four wheelchair users and one walker user. Daytime and nighttime scenarios were used in these exercises. Video cameras were used to record the subjects' delay times in the hotel rooms and the activities of the subjects while they were in the hotel corridors. The author was able to use the reported delay times in hotel rooms for each occupant and to model the disabled occupants based on their reported travel speeds. The detailed reporting of observations from the drills allowed direct comparison between the observed and predicted evacuation times for each participant. The model slightly overpredicted the evacuation times, but within 21 percent of the observed times, on average.

The staged evacuation exercise involved three floors of a high-rise office building, each occupied by 125-150 people. The occupants were instructed to move to the exit doors when the fire alarm sounded and to wait there for further instructions. In this evacuation exercise, the occupants were directed to leave the building approximately five minutes after the alarm first sounded. The evacuation was modeled in four phases -- the first three involving the evacuation of each floor's occupants to the stairway doors and the four phase involving their movement down the building's four stairwells.

The fourth phase of this exercise highlighted a problem with EXIT89 that will be addressed in the next set of enhancements -- the use of a single uniform distribution from which random delays are selected. The delay times at the stairs that were reported for the drill ranged to approximately 5 minutes, although the delays for the majority of occupants were much shorter. Because the model uses a uniform distribution to select random delays, though, a large number of very long delay times were set in the simulation, with the result that the model's distribution of delay times was vastly different from what was observed. This problem will be overcome by using distributions, such as a beta distribution, which can allow for outliers, but will not allow them to be over-represented in the analysis.

The other office building evacuation exercise allowed the demonstration of the newest features of the model -- the presence of contra flows and travel up stairs. In this evacuation, many of the occupants traveled up stairways to reach the exit closest to the designated meeting point outside. When modeling this evacuation, the contra flow option was used to simulate the impact of the flow of people traveling down the stairs with the flow of people who had traveled up from lower floors. The results of this simulation compared quite well with the actual evacuation exercise, although the total evacuation time was under-predicted by 35 seconds. (The last few evacuees in the drill left the building 66 seconds after the majority of occupants.) The variation in the number of occupants using each route was due to the variability in behavior that real people exhibit (for example, traveling against traffic away from exits, changing direction during their evacuation) that this model does not simulate. The results were very good, however, and demonstrate the effectiveness of EXIT89 in simulating a complex evacuation pattern in a high-rise building.

The last example provided the most interesting challenge to the model, because this single-story department store did not include any corridors or fixed barriers between spaces. There were 495 people in the store at the time of the unannounced drill. The actual evacuation exercise was completed in 2 minutes 45 seconds. The simulated evacuation ended in 1 minute 51 seconds. Because they were well assisted by staff, emergency exits throughout the store were well used. Although the results of this simulation were surprisingly good, EXIT89 works better with a more structured floor plan. The openness of the store layout allowed occupants to travel freely in all directions, while a more compartmented layout would restrict movement along better defined paths.

Although the model was originally written with high-occupancy, large-population applications in mind, the results of these exercises showed that the model can be effectively applied to smaller buildings. While the issues of queuing and crowdedness may not be important in smaller buildings, the evacuation of disabled occupants, the impact of exit choice and the variation in pre-movement times have universal relevance and can all be modeled by EXIT89.

CONCLUSION

EXIT89 is now capable of realistic treatment of:

- a building population with varying mobility capabilities;

- crowdedness that can occur during evacuations;
- the impact of training on efficiency of evacuation;
- obstructions that can impede travel during an evacuation;
- a range of pre-movement times, of whatever cause; and
- complex evacuation scenarios, including travel up stairs, and merging flows from different parts of a building.

EXIT89 remains a model of movement behavior and does not model either pre-movement behaviors or non-movement behaviors during evacuation. The model is available for practical use and additional evaluation in the fire safety engineering community.

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Evaluation Method of Egress Safety

Ichiro HAGIWARA
Building Research Institute, Ministry of Construction
1 Tatehara, Tsukuba-shi, Ibaraki-ken 305-0802, JAPAN

ABSTRACT

The Building Standard Law and Enforcement Order are revised, and performance criteria are introduced in Japan. Functional requirements of fire safety are clarified, and evaluation methods of fire safety are defined. In this paper, the outline of evaluation method of egress safety is presented. However, because we are still working on, the details of the method are not fixed and subject to change.

KEYWORDS: means of escape, performance-based code, egress safety

1. INTRODUCTION

In the present law and order, the egress safety is written in some groups of specifications. These are number of escape stairs, travel distance to stairs, stairs width, smoke exhaust equipment, limitation of lining materials and so forth, as shown in FIGURE 1. The framework developed in the MOC's SOPRO (comprehensive project for technical development) resulted that the functional requirements need some sets of performance criteria and evaluation methods for them. So, the evaluation method of egress safety is necessary as a part of the revised law and order. This will be one of the approved methods used for a verification of required performance. It means to allow a building plan, which does not meet the specifications for the egress safety.

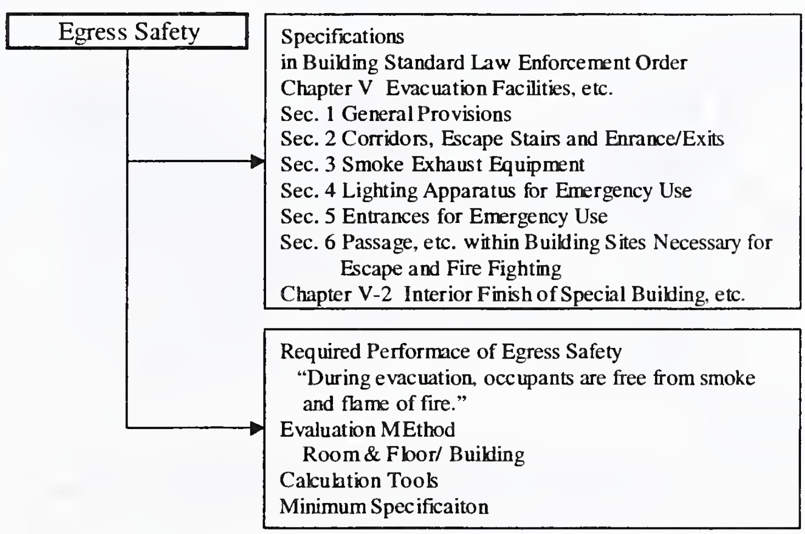

FIGURE 1 Framework of performance based egress safety

2. REQUIRED PERFORMANCE OF EGRESS SAFETY

In the performance-based evaluation, the design fire is introduced. The functional requirements of egress safety are "all occupants of a building are able to escape without difficulties and dangers from the design fire." So, required performance of egress safety are as shown below.

- During evacuation, occupants are free from smoke and flame of fire.
- There are some escape routes from any point to final safety place.
- It is easy to find out a safe escape route for unfamiliar occupants.
- There is no over queuing at any doors and junctions.
- ...etc.

Among these, the required performance of "free from smoke" is the most ready to be evaluated by using engineering tools. This is the required performance of egress safety, and the others are not subject to.

In Japan, it is recommended to calculate the egress time of a floor or a building larger than certain size. In a sense, it is valid for evaluating the performance of egress safety. However, it is lacking in taking account of important factors such as expected fire size, smoke management system, exit arrangement, occupant's character and so on.

This evaluation method consist of estimating smoke condition and escape condition. Smoke condition is estimated by taking account of the performance of smoke control equipment and the performance of smoke compartment such as walls and openings. Escape condition is estimated including the escape start time and the movement time. The evaluation is done by comparing the life threat time by smoke and the escape time in each escape route for each design fire.

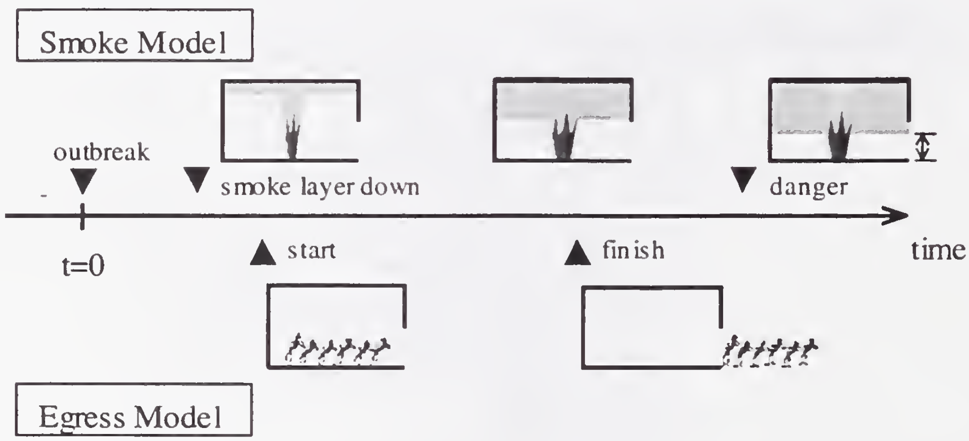

FIGURE 2 Concept of required performance of egress safety

3. EVALUATION METHOD

The evaluation of egress safety consists of two parts, escape from a fire floor and escape from a building. The escape from a fire floor includes the escape from a fire room. In each part, the life threat time by smoke is compared to the escape time. If the performance of egress safety is verified, some specifications such as travel distance, width of escape routes, and so forth will not be required.

3.1. Escape from a fire room

"The time needed for escaping out all occupants from a fire room" should be less than "the time of smoke layer descending down to the critical height in a room."

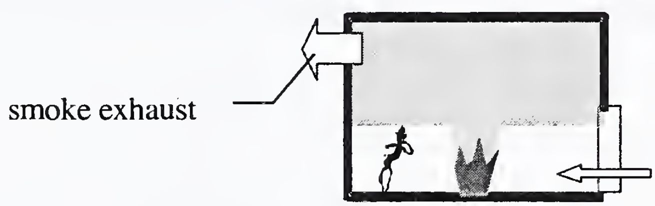

FIGURE 3 Escape from a fire room

3.2. Escape from a fire floor

"The time needed for escaping all occupants from the floor to the stairs" should be less than "the time of smoke layer descending down to the critical height in escape routes."

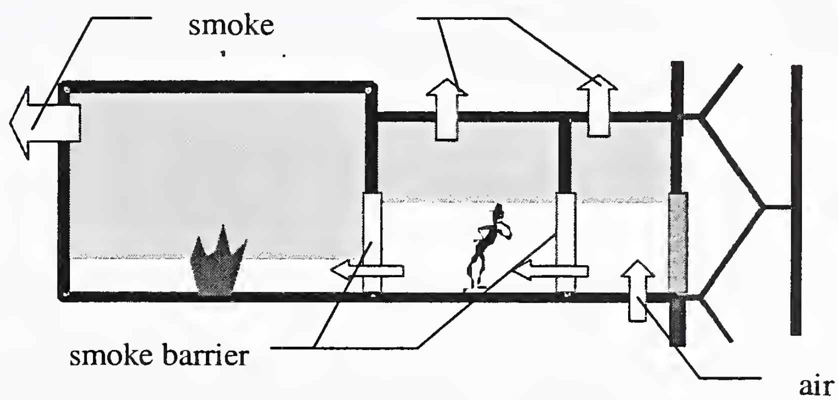

FIGURE 4 Escape from a fire floor

3.3. Escape from a fire building

"The time needed for escaping all occupants from the building to the outside" should be less than "the time of smoke spreading into stairs or other floors."

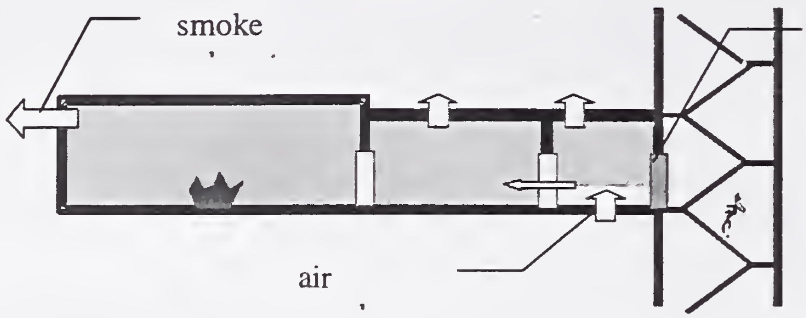

FIGURE 5 Escape from a fire building

4. CALCULATION TOOLS

As a verification method of the law and order, it is very important for practical use that calculation tools are simple rather than precise scientifically. From this point of view the following equations are developed.

4.1. Smoke time

The time of smoke layer descending down in a room is calculated by using the equation below. The smoke generation rate from a design fire M is determined by fire load density and room height, etc. The effective smoke exhaust rate E is determined by smoke exhaust capacity and efficiency. In the present Enforcement Order, the capacity of mechanical fan for smoke exhaust is required based on the area of smoke compartment as the specifications. In this method, the capacity of mechanical fan installed for the room is evaluated. The efficiency of smoke exhaust is calculated by taking account of smoke compartment size and smoke barriers depth, which are also limited by the present Enforcement Order.

$$t_{smoke} = \frac{A_{room} \times (H_{room} - H_{crit})}{M - E} \qquad (1)$$

Where
- t_{smoke} life threat time by smoke (sec)
- A_{room} room area (m^2)
- H_{room} room height (m)
- H_{crit} critical height of smoke (m)
- M smoke generation rate (m^3/sec)
- E effective smoke exhaust rate (m^3/sec)

Excluding a fire room in a floor, the life threat time by smoke is the sum of time calculated in each room and space between the room and a fire room. In these cases, the smoke generation rate M is given as smoke inflow rate through openings and gaps of the compartment. For example, it is assumed that openings fixed by airtight fire doors with self-closing device activated by smoke detector have almost no leakage of smoke.

4.2. Escape time

The escape time is simply the sum of starting time, travel time and clearing queue time. It is calculated by using the equation below. Concerning the travel time and clearing queue time, many experimental data and calculation models are available. In this method, this simple equation is used. The travel speeds on level, upward and downward on stairs are given. The effective flow rate is also given, but adjusted mainly by escape routes area from the room if the area is not large enough to accommodate all evacuees.

$$t_{escape} = t_{start} + \sum \frac{l_l}{v} + \frac{\sum pA_{area}}{\sum N_{eff} B_{avail}} \qquad (2)$$

Where

t_{escape}	escape time (sec)
t_{start}	escape starting time (sec)
l_l	travel length from any point to an exit in each room / space (m)
v	travel speed (m/sec)
p	occupant density (person/m^2•
A_{area}	area of each room (m^2□
N_{eff}	effective flow rate (person/m/sec)
B_{avail}	available door width (m)

The escape starting time is not understood clearly. In this method, the escape start time is given as the sum of two parts. Firstly, it is the time of transferring fire information. It is assumed that it depend on space size mainly. Secondary, it is the time of initial response to fire cues. It is assumed to depend on occupant type such as sleeping facilities and others.

$$t_{start} = [\mathit{time\ of\ information\ transfer}] + [\mathit{time\ of\ initial\ response}] \qquad (3)$$

5. CONCLUSIONS

The evaluation method of egress safety is developed for revising the Building Standard Law and Enforcement Order in Japan. It is a first step of performance-based evaluation of egress safety. However, it is insufficient that egress safety performance is defined only as escaping free from smoke. It should consist of various required performances, such as redundancy of escape routes, easy way-finding and so forth. For developing more reasonable performance based evaluation, more studies on egress safety are necessary.

PERFORMANCE-BASED CODES AND STANDARDS

Progress and Overview of Performance-based Codes and Standards in Japan

Makoto TSUJIMOTO
Nagoya University
Nagoya, 464-8306 JAPAN

Shuitsu YUSA
Building Research Institute
Tsukuba, 305-0802 JAPAN

If you search the item: " 性能規定化 : Performance-based "& " 法 : regulation " by Yahoo Japan, you can hit some 300 pages. About 60% of them are related to the amending process of Building Standard Law. And in the rest, there are no specific movements to amend the codes into performance-based except the technical standards on gas and electric facilities.

So the case of Building Standard Law of Japan (BSL, hereafter) occupies an important position among the performance-based transformation in Japan.

This paper summarizes the circumstances of these currents as follows,

a) The end of fire codes of BSL

b) The process to the performance-based code

c) The present condition of Building Standard Law

d) The present condition of Fire Services Law

a) The end of fire codes of BSL

It is natural to accept that the end of law such as Building Standard Law, is to realize the society as Roscoe Pound mentioned (1921),

"One such postulate, I think we should agree, is that in civilized society men must be able to assume that others will do them no intended injury -- that others will commit no intentional aggressions upon them." [1)]

In the field of building and construction, for example, to built the fence which is easy to collapse in case the foreknowable force is operated from outside, or to turn out a fire resulting in injury or death in case the fire protection manager of common building does not take proper care against fire, is the aggression.

In each case, the judicial decision according to the Civil Law or the Criminal Law was given using BSL or FSL as a standard of judgement.

In this context, the fire codes of BSL are the criteria to judge for the fundamental Laws (e.g. the criminal law, the civil law), the end of which is to realize the society that others will commit no intentional aggressions upon them .

(b) The process to the performance-based code

Then, what is "the intentional aggressions" in such regulation as the fire codes whose aim is to decrease the fire damage? The fire codes of Building Standard Law had no proper answer to this question at the time of legislation, 1950, because they were the patchwork of existing regulations written in prescriptive form. And Fire Services Law(1948) has the same root.

On the other hand, new regulations were legislated in 1970's with the background of the bad environment of cities or factory area and the elevation of the right of claim. They are, for example, Air Pollution Control Law (1968), Water Pollution Control Law(1970), Offensive Odor Control Law(1971). And they had a clear definition of "the intentional aggressions".

In these new laws, "the aggressions" are defined by the physical property such as the energy of noise or the concentration of contamination, and its criteria. Compared with them, fire codes didn't have the clear definition of the aggression by fire, and the intention of the criteria is obscure because of the prescriptive form.

This is the reason why the amendment to performance-based code was required for from the standpoint of legislation in Japan.

Besides, there were more additional causes to the amendment of the Building Standard Law on July, 1998.

One is the development of new technology. As shown in Fig.1, the fruits of So-Pro on "Development of the Assessment Method of Fire Safety Performance of Buildings (1982-87)" resulted to increase the number of buildings which were accepted through the route of Article 38 of BSL. In this way, the use of fire resistant steel or the smoke control by accumulation in the upper vacant space of atrium became popular. As the system is getting greater success, limitations are becoming apparent. Article 38 accepts alternative design solutions that are equivalent to the specifications in the code without specifying the objectives. Lacking the information on the objective, or on the intentional aggression mentioned above, it is sometimes difficult to discuss the equivalency between "specification A" and "specification B". That is why we need a performance-based approach.

And the other driving forces for amendment of BSL are as follows;

- to follow with the worldwide trend to amend the building codes from prescriptive to performance-based, which Building Act (1984) in England initiated
- to take a measure logically against the strong requirement from United States and Canada for permission of the 3-stories wooden houses

(c) The present condition of Building Standard Law

Judging from the legislation process mentioned above, it is clear that the purpose of the amendment of fire codes is to make clear the definition of "aggression by fire" and the acceptable

criteria of them. Translating it to the words of Fire Safety Design, what to do is to prepare the design fire and to make clear the functional requirements.

The basic concept of design fire is similar to seismic wave input used in the seismic resistance design. But in this concept, the frequency of fire occurrence is not considered. The frequency changes with occupancy of the building, and decreases as the scale of the building increases when the occupancy is office use.[2)]

Using the information of design documents at application (the information of combustibles from the occupancy and the lining, and the geometry of the room and the fire resistance of enclosure from the plan), the design fire shows the fire growth (typically t^2-growth, including flashover onset), followed by either fuel surface controlled or ventilation controlled fire[3)].

Next to do is to make clear the functional requirements of fire safety, which are evaluated by using the design fire. About this, the performance-based framework of the building fire safety in Fig.2 was shown as the result of So-Pro “Development of assessment methods for fire safety performance (1993-98) ”

The functional requirement of the fire safety design is summarized into five terms “prevention of fire initiation”, “provision of means of egress”, “prevention of collapse”, “provision of fire base and access” and “prevention of fire spread to/from adjacent buildings”.

The evaluation method and its criteria for each functional requirement is called for. This time, two verification methods, Evaluation Methods of Egress Safety and Structural Fire Resistance are prepared by BRI.

The draft of the revised Enforcement Order of BSL is now on the HP (http://www.moc.go.jp/policy/publiccomment/publiccomlist.htm) because of the period of public comments. And the ministerial notifications concerning with the Enforcement Order will be announced by at late April 2000, and be enforced by June 2000. About the detail of the evaluation methods and the coordination between existing codes and new ones, please refer the papers by Yusa. Hagiwara and Ohmiya on this Panel.

Through this movement, there are two topics. One is the hot eyes which structural engineers turn to the Evaluation Methods of Structural Fire Resistance. With this method, structural engineer can design the structure in the same way as earthquake or wind.

The other is the continuity to FLS. If FSL adopt the same concept of design fire, the fire fighting equipment can be evaluated on the same model. For example, the estimation of operation time of fire detectors started experimentally using the heat source which simulates t^2-growth.

(d) The present condition of Fire Services Law

According to Fire Services Law (FSL, hereafter), about 10 cases of deregulation have been done in 1995-98, for example,

· deregulation about the ratio of public space in underground market

· deregulation about the number of sprinkler heads which should actuate in fire

As the first step to performance-based code, Fire & Disaster Management Agency, Ministry of Home Affairs started the committee in 1999, " Development of Fire Safety Measure against Fire Risk of fire prevention property (Shobo So-Pro) "

The ends of committee are

- to assess the fire risk of fire prevention property considering the progress of technology
- to examine the existing fire safety measures systematically from the viewpoint of technology and to verify their effectiveness.
- to survey the fire safety measures about the possibility of development, which can synthesize fire fighting equipment, fire loss prevention and control management, structure type of building, and so on.
- to develop the assessment methods which correspond to each area as follows, and to verify the new fire safety technology based on performance by them,

① Prevention of fire origin & flame retardation of materials

② Fire detection & fire alarm

③ Fire suppression

④ Evacuation safety & support of fire fighting

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4) Yamada, T., Harada, K., "Progress and Overview of Fire Engineering Tools in Japan", 14th US-Japan Joint Panel on Natural Resources (UJNR) Panel on Fire Research, (Tsukuba), 1998

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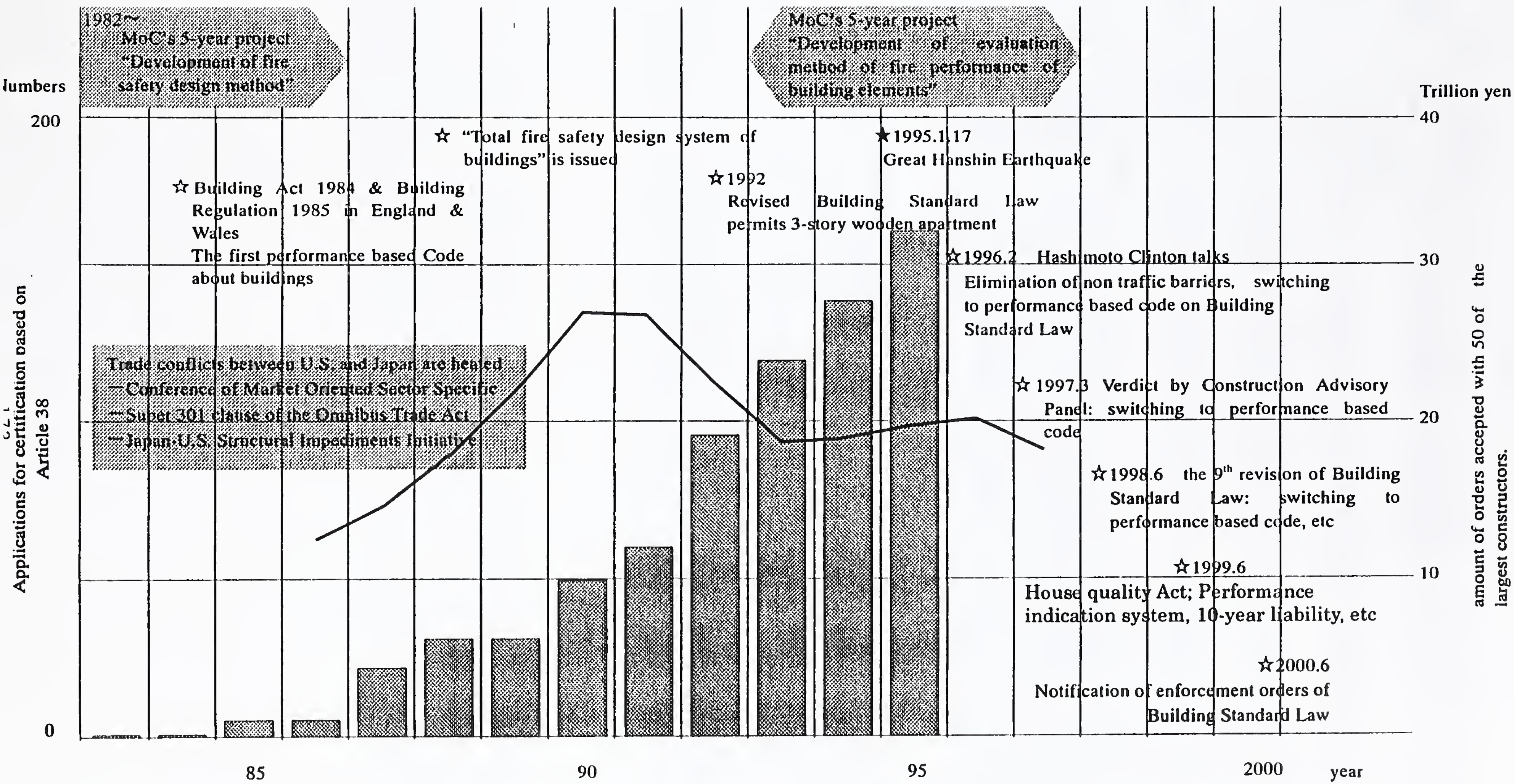
Figure 1. Background



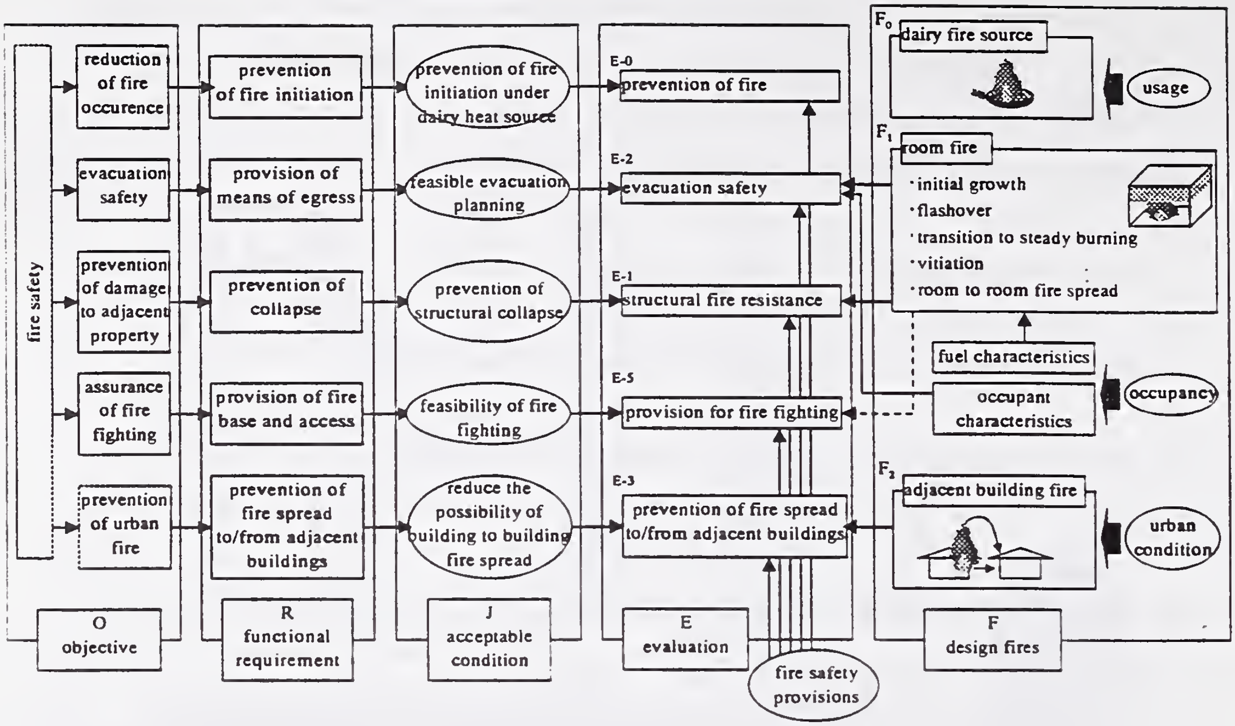


Figure 2 An example of the performance based fire safety design (evaluation) system

Developments in PBD Technical Infrastructure: SFPE Engineering Design Guide and Engineering Practice Guides

Craig Beyler, Ph.D.
Technical Director
Hughes Associates, Inc.
3610 Commerce Drive, Suite 817
Baltimore MD 21227

ABSTRACT

Performance based design will require improved technical infrastructure. This paper describes the ongoing efforts of the Society of Fire Protection Engineer to develop this technical infrastructure. SFPE Engineering Design Guide is a performance based engineering process document and Engineering Practice Guides provide documentation of analysis methods with established limitations and known accuracy. The first such guide assesses methods for predicting radiation from pool fires.

The process of identifying methods and data, and evaluating the methods for predicting radiation from pool fires was a straightforward but intensive process. The process worked well and the results provide a model for similar activities in the future. More refined methods for setting the safety factor based on a statistical approach need to be considered for the future.

The effort to date represents merely the very first steps in a process that needs to occur on an international scale. Some cooperative arrangements have been made, but more is needed. As there have not been any documents generated through the cooperative relationships up to this time, the effectiveness of the cooperation is a matter for speculation.

INTRODUCTION

The Society of Fire Protection Engineers has made a commitment to develop engineering practice documents. These documents are intended to evaluate analytical methods for use in fire protection engineering and to provide guidance in developing the input data required for the use of these analytical methods. In addition SPFE has developed the *SFPE Engineering Guide to Performance-Based Analysis and Design of Buildings,* which provides a framework for developing and assessing fire protection strategies to meet fire and life safety objectives.

ENGINEERING PRACTICE DOCUMENTS

The 1991 Conference on Fire Safety Design in the 21st Century[2] identified a number of strategies to realize the goal of developing a first generation performance-based building code which are directly related to developing the technical infrastructure required for performance-based design. These included making innovative engineering tools readily available in a usable, and establishing a mechanism for third-party validation of new (and old) engineering tools.

SFPE has created several task groups in support of the development of the technical infrastructure required for performance-based design; Computer Model Evaluation Task Group, Engineering Practices Task Group, and Performance-based Fire Safety Analysis and Design Task Group.

The Computer Model Evaluation Task Group has been developing an evaluation document for DETACT, the detector activation model developed by NIST based on technology which is now two decades old. The goal was to develop this first document on a simple but widely used computer model. While the TG has had some support from NIST, the efforts of the task group are that of volunteers. They have been working for several years and will soon release their first document. Given the simplicity of DETACT relative to other widely used models, this effort has shown that this will be a very long-term project.

The Engineering Practices Task Group's scope was to develop engineering practice guidance documents. The TG chose to work on the prediction of radiation from fires and its effect on targets because it is relatively simple. Subsequently, several task groups on other topics have been formed. The initial scope of the fire radiation document was limited to pool fire radiation, effects of radiation on humans, and ignition of combustibles by radiation. At this time the radiation from pool fires document has been published and the other two documents are complete and will be released in 2000. The goal of the documents is to review engineering methods available; including the data requirements and data sources, the assumptions of the method, the validation available for the method, and the limitations of the method. The engineering methods were compared with available data, and where possible, safety factors for use with the methods were developed. On a volunteer basis, this is an extraordinary effort. The magnitude of the work required to provide this treatment for all the engineering methods available is tremendous.

Academic institutions have had a significant role in the development of practice guides to date. This involvement has been through very small grants and through volunteer activities. Given the value to the educational missions of academia, the need for extensive work in evaluating engineering methods, and our profession's need for these documents, we need to find mechanisms to finance student research, which supports engineering practice guide development. While the development of engineering practice guides should include broad input from members of the engineering profession, the level of effort to complete evaluations of available engineering methods is beyond what can reasonably be expected to be completed through only volunteer efforts. Graduate students in Fire Protection Engineering are perfect candidates for this work. It

supports the student's educational needs and graduate students are most capable of performing the work under appropriate direction.

Recognizing the need for engineering practice guides and the immensity of the task, the International Fire Safety Institute (IFSE) Working Group on Fire Engineering Guidance was convened in 1998. It was agreed that the member organizations (the Society of Fire Protection Engineers, the Australian Society of Fire Safety (SFS) and the UK Institute of Fire Safety (IFS)) would cooperative pursue development of engineering practice guides. The purpose of IFSEI is to support the globalization of the fire protection engineering profession and provide a forum to facilitate international collaboration. One of the activities being undertaken by IFSEI is international cooperation in developing engineering tools and data. This effort recognizing that codes and process would likely vary from country to country, but engineering tools and data would be universal. Therefore, IFSEI members agreed to collaborate on the development of fire safety engineering guidance by establishing a lead organization, with the remaining organizations acting as "peer reviewers" and identifying data from within their countries in the area.

Each of the three organizations would take primary responsibility for individual guides so that the large universe of guides that are needed will ultimately be authored via one of the three organizations. The first five projects undertaken by IFSEI were:

1. Room of origin fire hazards (SFPE lead),
2. Structural fire resistance (SFPE lead),
3. Occupant behavior and egress (IFS lead),
4. Risk, reliability, uncertainty (SFS lead), and
5. Fire brigade/department response (SFS lead).

Additional participation from other organizations is being sought. This international arrangement will go a long way to avoid duplication of efforts and can lead to documents with wide international acceptance. NFPA, ASCE, and many others, have roles to play in this process.

The Engineering Practice Guide and Computer Model Evaluation Task Groups are pursuing goals articulated in the 1991 Conference on Fire Safety Design in the 21st Century[2]. The question at this stage is whether they are making sufficient progress and are volunteer task groups actually capable of completing the needed work. The evidence at this time is that while credible documents are being developed, the pace of the ongoing work is too slow, and the scope of ongoing work is too narrow. The process needs to be supported financially to get the work done in a timely manner. The modest financial support to date has been vital and much more support can and would be effectively used to provide the documents, which are sorely needed.

The Performance-based Fire Safety Analysis and Design Task Group has made significant progress in developing a process document for performance-based design. The document is complete at this time and will be published by NFPA in 2000. This document provides a roadmap for the design team, the AHJ, and other interested parties. It defines the

conceptual design process and provides guidance on documentation of the conceptual design. It draws upon the international experience (most clearly from the UK and Australia) in developing design process documentation for performance-based design. While this is a process document and contains no technical basis for design, it does define the process by which performance-based design is incorporated into the conceptual design process. International experience has indicated that such documents facilitate performance-based design by providing a clear definition of roles and process in the conceptual design process.

The Performance-based Fire Safety Analysis and Design Task Group differs from the Engineering Practice Guide and Computer Model Evaluation Task Groups. First and foremost, the document produced by the Performance-based Fire Safety Analysis and Design Task Group is a process document, and as such does not contain detailed engineering methods and rigorous evaluations of these methods. While the task of developing the process document was clearly challenging, the depth of the work is far less than in evaluations of engineering methods. Nonetheless, the development of the process document was funded by NFPA through a contract with SFPE at a level well above that available to the Engineering Practice Guide and Computer Model Evaluation Task Groups which received funding from NIST through a grant to SFPE.

The reality of the situation is that money makes the process work much faster. There is no doubt that without funding these documents can be produced, but they will take far too long without financial support.

It is equally clear that international collaboration is essential. There is no need for the documents to be national in nature, since performance requirements are not included in the documents. The documents simply describe and evaluate engineering methods and their technical applicability. Since the task of creating these documents is greater than any nation or organization can support or perform, the ongoing efforts to internationalize the process are important to making timely progress. So far, international cooperation has been good, but the scope of nations and organizations directly involved is limited.

AN ENGINEERING GUIDE: RADIATION FROM POOL FIRES

The goal of this engineering guide is to provide methods for predicting the radiation from a pool fire to a target outside the pool fire. This is a relatively simple problem, which has been studied over many decades. The strategy employed by the task group was to identify calculation methods available in the literature and assess each method with regard to the data requirements, data sources, model assumptions, model validation, and model limitations.

In order to perform these assessments, the task group also identified all relevant heat flux measurements performed for targets outside of pool fires. The scope of the models and assessment was limited to pools greater than one meter in diameter. Fourteen experimental investigations were identified. These included 32 experiments with a total of over 100 data points. Pool diameters ranged from one meter to 50 meters, and the fuels included kerosene, gasoline, heptane, crude oil, JP fuels, LNG, methanol, and toluene.

Four calculation methods were identified in the literature. The simpler methods included a power law correlation and the point source model. Two methods based on cylindrical radiators were identified and evaluated.

The evaluation of the methods is organized as follows:

1. Method description,
2. Data requirements for the method,
3. Data sources available,
4. Method assumptions,
5. Method validation,
6. Method limitations, and
7. Recommended factor of safety for the method.

The goal of the first four sections is to provide a clear description of the method, its assumptions, and what data is needed for the calculation. For the cylindrical radiator models graphical methods for assessing the configuration factor are included for the convenience of the user. The core of the evaluation is the method validation section. Here the available database is used to evaluate the performance of the method. The primary method of evaluation used in this guide is plots of predicted vs. measured heat flux. Different types of data are identified by the symbol used to allow an overall assessment of the method as well as information as the scenarios that the method has the greatest difficulty predicting. The limitations section uses the information provided by the method developer as well as the validation results to identify when and where the method can be credibly applied. The safety factor section provides an indication of the factor of safety required in the method t achieve conservative predictions, based primarily on the method validation section. Finally there is a summary section which provides general recommendations regarding the selection and use of methods.

The results of the evaluation were somewhat surprising. The preferred method for heat fluxes below 5 kW/m^2 was the simple point source model. This would include applications where equipment damage or effects on humans are the hazards of concern. The simple point source method performed better than the more complex cylindrical radiator methods. The comparison is somewhat unfair, however, since the point source model had no associated method for determining the radiative fraction. A correlation of the radiative fraction as a function of pool diameter was developed using the validation data set. As such, a parameter in the model was assessed through a correlation based on the validation data set.

For heat fluxes greater than 5 kW/m^2, the preferred method was that of Shokri and Beyler cylinder method. There is no doubt that the method could be further optimized, but the goal of the task group was to evaluate existing methods, not to modify or create new ones.

All the methods evaluated required a factor of safety of two in order to conservatively predict heat fluxes. However, the preferred methods provided better correlation of the data and as such did not overpredict as greatly as the other methods evaluated.

CONCLUSIONS

The process of identifying methods and data, and evaluating the methods for predicting radiation from pool fires was a straightforward but intensive process. The process worked well and the results provide a model for similar activities in the future. More refined methods for setting the safety factor based on a statistical approach need to be considered for the future.

The effort to date represents merely the very first steps in a process that needs to occur on an international scale. Some cooperative arrangements have been made, but more is needed. As there have not been any documents generated through the cooperative relationships up to this time, the effectiveness of the cooperation is a matter for speculation.

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OUTLINE OF REFORMING THE BUILDING STANDARD LAW IN JAPAN

Shuitsu YUSA
Building Research Institute

Makoto TSUJIMOTO
Nagoya University

INTRODUCTION

The Draft Cabinet Order or Enforcement Order related to fire safety has opened for public comments on February 14,2000, following "The Law to amend the Building Standard Law" issued on June 1998. This revision partly includes recent progress in the comprehensive studies aiming at performance based fire safety design method made by two MOC (Ministry of Construction) ***Sopuro.*** These are "Design of Total Building Fire Safety (conducted in 1982 through 1986;Fire safety Sopuro) and "Development of Assessment Method for Fire Performance of Building Materials and Structures (1993 through 1997;Fire Test Sopuro). The technical studies in view of the revision of fire safety provisions in Building Standard Law and its associated government orders (model building codes) are being carried out by Building Guidance Division of MOC with technical support by BRI fire research staff. The purpose of the Fire Test Sopuro was twofold, i.e. to develop new fire test method which can be globally accepted and can measure the data useful for fire safety engineering tools and to improve and complete the fire safety design method introduced as the result of Fire safety Sopuro. The fire test method consisted of material combustibility test, fire resistance tests and opening assembly tests. The harmonization with ISO test method was stressed in the former two. As for improvement and completion of fire safety design method, the criteria for compliance verifications to the requirements are newly developed or reconsidered. The design fires were reconsidered and practical FSE tools, often computable by the use of hand calculator, were developed. The related Notifications of MOC, which include prescriptive codes and FSE tools, will be published by June this year.

This paper is written to introduce the background and outline of revised draft Enforcement Order of the Building Standard Law focused on a performance-based code in the field of fire safety. As a result of the work for change to performance-based criteria, the outline of structural fire resistance assessment and performance of egress safety is described. The Provision related to materials is in the appendix

BACKGROUND

To changing the Building Standard Low towards performance-based standard is world-wide movement and there are two main reason i.e., the technological limitation of prescriptive criteria and new knowledge in fire safety engineering to correspond with internationalization of fire safety technology.

Regarding the change of Building Standard Law (legal part) last June, there are various movements under "performance-based criteria." Disregard the movement outside of Japan, three types of movements are discussed regarding "performance-based criteria". At first, change various technological criteria to harmonize ISO or replace to ISO then change the law, which are related to it. There is a group calling this as process for changing to performance-based criteria but there are some "prescriptive criteria" in ISO standards, which do not have any relationship to performance and it should be pointed out as process to the internationalization.

Second, because of the word "performance" has many meaning, it is interpreted as "the performance-based design"(Build by designer and/or contractor and user agreed on performance level of building. The system that designer and/or contractor are required to take responsibility of product liability based on agreed performance level.)is supported by this criteria.

Third, this is the main subject of this paper. The current law, which stated by specification, is so much out of date, to change performance (function) base has to start from the area that is technically clear. But in actual work including internationalization and it has to consider the continuity to the law. So, I have to admit that there may be some contradiction regarding performance-based criteria.

1. Performance-based evaluation

One of main change in the Building Standard Law is to introduce the regulation that if certain level of performance is satisfied, you may use various material, equipment and structural system. The performance-based criteria object to fire safety can make a choice by item from which states in the text of performance criteria, as long as you are able to show the way of assessment for performance and judgement criteria. Specifically as indicated in figure 1 below, assessment for the structural fireproof will be introduce due to change part of the fireproof regulation (Article 27: Special Buildings Which Ought to be Fireproof or Quasi-fireproof Buildings, Article 61-62: Buildings in fire protection Districts) and Prohibition of large wooden structure (Article 21). Assessment of egress safety performance regulation will be introduced corresponding to an evacuation facility, smoke exhaust system or interior material limitation. Hereafter we call them performance rout. Even though the performance-based methods are introduced, basically the prescriptive methods will be remained after some rationalization as an alternative. To choose from performance-based method or prescriptive method is depend upon designer' decision, but either way the content of regulation will be same. A part, which does not correspond to performance-based method, will remain as existing prescriptive method. The prescriptive method, which stays in new law will be rationalized the testing method or related items and replaced by corresponding ISO standards and seeks to harmonize with performance-based assessment. Specifically testing method of materials and fireproof is changed to rational method which is based on ISO standards and the new testing method will be introduced to the area of which did not have any specific testing method or only has prescriptive method.

BEFORE	AFTER
Codes on Fireproof buildings (Article 27: Article 61-62) Prohibition of large wooden structure (Article 21)	EVALUATION METHOD OF STRUCTURAL FIRE RESISTANCE - Examine the building does not collapse/spread fire by fire - Examine the integrity of the structural part by assume the nature of fire.
Technical standards for egress, smoke exhaust & interior finish limit etc. (Article 35)	EGRESS SAFETY EVALUATION METHOD - examine the evacuation rout during fire - The application of egress safety performance-based method is escape from a fire & escape from a building. The shaft enclosures, such as stairs will be remain as specification-based method.

Fig. 1. The area which change to performance-based method

Standards for fire prevention materials	- Rationalization of testing method for materials (harmonization to ISO) - Regulation for technical standards regarding performance)
Fireproof-performance required by fireproof construction Fireproof-performance required other structure	- harmonization to ISO regarding fireproof testing method (ISO 834) - Regulation for technical standards regarding performance
Prevention of fire spread from roof Prevention of fire spread from sofit of roof and opening	- New testing method for leaping flames - Prepare the new testing method for required performance.

Fig.2 Remain as prescriptive regulation but harmonizes to performance-based regulation with some rationalization.

2. Outline of performance-based evaluation

2.1 Constitution

The function needed for fire safety of building is following five points: prevention of fire initiation, provision of means of egress, prevention of collapse of building, provision of fire base and access and prevention of fire spread to/from adjacent buildings. To reach the ideal performance level is to introduce the performance standard for each item. This is the first step for the change. Mainly two items in above, i.e., egress safety and prevention of collapse of building are preparing as regulation of performance-based criteria.

2.2 Design Fire

It is very important for determine the prediction method of fire behavior to introduce performance-based approach. We are not thinking to consider the frequency for outbreak of fire in depth at this point. To assume the origin of fire is equivalent in engineering terms to express the process of fire growth in architectural space. But it is very difficult to assume how the combustible material (interior finishing, contents, and fixed furniture) burns in space. In the Enforcement Order, simple equations are shown for calculation method and actual equations will be described in the Notification. Fire duration time for evaluation is calculated using heat release rate, total heat release of fuel, under conditions of a room.

3. Performance-based evaluation in the Draft Enforcement Order

3.1 Evaluation Method of Structural Fire Resistance

Performance-based evaluation method of structural fire resistance assesses "The structure must not collapse." The possibility for using structure after fire is out of scope, because if the fire is only limited area then it can be assessed the durability diagnosis and repair can be done.

According to the Building Standard Law, the performance requirements for principal building elements of fireproof buildings are as follows:

(1) Principal building parts of fireproof buildings

① of fireproof construction, or

② of construction that meets the technical requirements laid down by Enforcement Order concerning their ability to withstand the heat until the fire is extinguished

The performance-base method is applied for above ②. Performance requirements are as follows;

① The following requirements must be satisfied when exposed to heat generated by a fire likely to take place within the building:

(a) Bearing walls, columns, floors, beams, roofs and stairs must not be damaged under the stress of dead or live load.

(b) Walls and floors must possess heat insulation property.

(c) Exterior walls and roofs must possess flame insulation property.

② Exterior walls must satisfy the following requirements when exposed to heat caused by fire taking place outside of the building:

(a) Exterior walls constituting bearing walls must not be damaged under the stress of dead or live load.

(b) Exterior walls and roofs must possess flame insulation property.

"Non-damage ability" means that the building part in question suffers no damage detrimental to structural strength. And this is part of performance evaluation. "Heat insulation property" means that the temperature of surface other than the surface exposed to heat will not rise up to a point where combustible materials touching any of the surfaces start burning. "Flame insulation property" means that the part in question suffers no damage such that flames become visible from the outside of the building.

Outline of Fireproof property verification method is as follows;

① Regarding indoor fires, the predicted duration of a fire in each room of a building and the period of time for which the principal building elements of the room concerned can withstand the fire shall first be obtained. The latter is called "Retaining Fireproof Time (Critical Time, hereafter) of Indoor Fire." Then it shall be confirmed that the former is less than the latter.

(a) The duration of fire shall be calculated by dividing the total calorific value of combustible materials found in the room concerned by rate of heat release. The total calorific value shall be calculated according to the use of the room and the interior materials used in accordance with the method laid down by the Minister of Construction. The rate of heat release shall be calculated according to the use of the room and the shape of openings, etc. in accordance with the method laid down by the Minister of Construction.

(b) The Critical Time of Indoor Fire of principal building elements shall be calculated according to the structural type, the stress generated in the elements due to dead load, etc. and changes in temperatures resulting from an anticipated fire, by means of method specified by the Minister of Construction.

② Regarding outdoor fires for exterior walls. (Omission)

It is possible to interpret the testing results for building design condition. The testing method can be defined as the way to get property value of materials/components to assess architectural design in the performance-based method. It is not yet established the technological method to rationally control the fire, which burned through two stories at this point of engineering knowledge. Therefore even this method has limitations. It means that area of fire must not spread through floors. Prevention of spread of fire is always required for going up stairs through openings or shafts.

Example of evaluation is introduced in "Evaluation method of structural fire resistance" by Ohmiya et al for this 15th UJNR meeting.

3.2 Evaluation Method of Egress Safety

The functional requirements of egress safety are that all occupants of a building are able to escape without difficulties and dangers from the design fire. The performance of "free from smoke" is selected for evaluation using engineering tools and defined as the required performance of egress safety.

The evaluation method consist of estimating smoke condition and escape condition. Smoke condition is estimated by taking account of the performance of smoke control equipment and the

performance of compartment walls and openings. Escape condition is estimated including the escape start time. The evaluation is done by comparing the life threat time caused by smoke and the escape finish time. In the Enforcement Order, the evaluation of egress safety consists of two parts, escape from a fire floor and escape from a building. The escape from a fire floor includes the escape from a fire room. In each part, the life threat time by smoke is compared to the escape finish time. If the performance of egress safety is verified, some specifications such as such as number of escape stairs, travel distance to stairs, stairs width, smoke exhaust equipment, limitation of lining materials, etc will not be required.

Escape from a fire room, from a fire floor, from a fire building and calculation tools are introduced in "Evaluation method of egress safety" by Hgiwara for this 15th UJNR meeting.

CONCLUDING REMARK

After the revision of the Building Standard Law and the Enforcement Order, it is expected that, on one hand, new technology that was so far treated in Article 38 (deleted in this amendment) will meet clear objective and be verified under the Law. On the other, to give impact to progress performance-based evaluation and development of related engineering tools in the field of fire safety. This could be a beginning of epoch making although there remain some inconsistency which should be solved.

(Reference)

1) Tsujimoto, M., Hagiwara. I., Harada. K., Takahashi, W., Takeichi, N., "Evaluation method of fire prevention and evacuation code in Building Standard Law". Fire, Vol. 49(1), pp.7-15,1999

2) Ohmiya, Y., Yusa, S., Harada, K., "Evaluation method of structural fire resistance". presented at 15th UJNR Panel on Fire Research

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II REVISIONS RELATED TO FIRE PREVENTION

1. Improvements to technical standards related to materials, structures, etc.

   (1) Provisions related to materials (noncombustible, quasi-noncombustible and fire-retardant materials)

   In response to Article 2, item (9) of the Building Standard Law which provides that noncombustibility (i.e., performance required of noncombustible materials) and the technical requirements concerning such performance shall be laid down by Enforcement Order, Article 108-2 of Enforcement Order establishes provisions concerning such noncombustibility and technical requirements applying thereto. Since every regulation thereunder is controlled by Enforcement Order, the performance and requirements in respect of quasi-noncombustible materials and fire-retardant materials as defined by Enforcement Order shall likewise be clarified. The performance required of each category of materials shall be as follows.

<Technical requirements for noncombustible materials>

When exposed to the flame and heat of normal fires the material concerned must satisfy the requirements as well as withstand the heat for a duration shown in the following table after heating has started:

Type of material	Duration	Requirements
Noncombustible material (per Enforcement Order, Art. 108-2)	20 minutes	* Does not burn * Does not suffer damage detrimental to fire prevention * Does not generate smoke or gas that obstructs evacuation
Quasi-noncombustible material (per Enforcement Order, Art. 1)	10 minutes	Ditto
Fire-retardant material (per Enforcement Order, Art.1)	5 minutes	Ditto

(2) Provisions related to construction

EVALUATION METHOD OF STRUCTURAL FIRE RESISTANCE

Yoshifumi OHMIYA
Building Research Institute, MOC
1 Tatehara, Tsukuba-shi, Ibaraki-ken 305-0802, JAPAN

Shuitsu YUSA
Building Research Institute, MOC

Kazunori HARADA
Kyoto University

1.INTRODUCTION

Traditionally, the Building Standards Law of Japan has included a large number of prescriptive requirements in the form of obligatory classification requirements for components and structural elements. The regulation concerned with fire building safety is no exception to prescriptive law. However, the general aim has been expressed explicitly, even if not very clearly. Recently, fire safety code of building is changing from prescriptive to a performance-based approach in several countries. In Japan, for the performance-based approach, the verification tool by way of fire safety design system is just developing.

A case-study was carried out to examine the feasibility of a performance-based fire safety design system developed in Japan. This system would have the capability for leading to flexibility for designing buildings, to deal with new types of materials, elements or buildings etc. Especially, the evaluation method of structural fire resistance was indicated in this report.

2.EVALUATION METHOD FOR DETERMINING STRUCTURAL FIRE RESISTANCE

The evaluation of structural fire resistance is a method by calculation and experiment. The former means a method using simple equations and computer simulation and the latter means experiment by ISO 834 and so on. In this report, a calculation method composed of closed-form equations was shown. As for structural fire resistance of buildings estimated by this system, it is necessary to calculate temperature in fire compartment and service load of structural elements. It is possible to evaluate performance of structural fire resistance by using the result of these calculations. These closed-form equations were developed by Japanese researchers, in order to verify fire safety of building design according to performance based concepts[1]. The formula proposed in this report is as follows:

2.1□Prediction method of Fire Behavior

1 Fuel Surface Area

Fuel carried in buildings can be divided into two types, namely live load and dead load. The surface area of fuel may affect fire behavior within a compartment. As a result of investigations of live load in Japan[2], it was found that its surface area depends on its density, approximately. Namely fuel surface area is given by:

□ $A_{fuel} = 0.214 \times q_l^{1/3} \times A_{floor} + \sum \phi \times A_{fix}$ 1)

The fuel surface area in this equation indicates the sum of live load and dead load within a fire compartment. In this equation, q_l indicates the heat release rate per unit fuel surface area of live load, □ indicates the oxygen consumption coefficient of dead load. These values were derived from the following tables.

Table 1□ Heat release rate per unit fuel surface area of live load : q_l□

Occupancy	HRR□q_l□MJ/m^2□
Meeting room	160
Seating space of theater and assembly room	240
Guest room of hotel	240
School room	400
Stage of theater and assembly room	480
Selling floor of department store	480
Seating space of restaurant	480
Office room	560
Residential room	720

Table 2□ Oxygen consumption coefficient of dead load :□ □

Class of interior material	Oxygen consumption coefficient □
Noncombustible material	0.1
Fire retardant material□excluding noncombustible material□	0.2
slow burning material□excluding noncombustible material and fire retardant material□	0.4
Material excluding above	1.0

2 Effective Ventilation Parameter

To predict fire behavior, it is important to estimate the rate of air inflow from openings to fire compartment. In regime of ventilation controlled fire, the air inflow rate from openings depends on the size of opening, so-called ventilation parameter. In this estimation method, when there is more than one opening in the walls of a compartment and the height of openings is at the same level, or when there is one opening, the ventilation parameter is derived from the next equation.[3)]

a□In case the height of openings is at the same level, or there is one opening,

$$□\left(A\sqrt{H}\right)_{eff} = \sum_k B_{op,k} H_{op,k} \sqrt{H_{op,k}} \qquad 2□$$

Furthermore, when there is more than one opening in the walls of a compartment and the height of openings is at different levels, the ventilation parameter is calculated from the next equation.

b□In case the opening height is different,

$$\left(A\sqrt{H}\right)_{eff} = \begin{cases} 6.4A_a\sqrt{h_{as}} & (A_a/A_s \le 0.25) \\ 3.2\sqrt{A_a A_s}\sqrt{h_{as}} & (0.25 \le A_a/A_s \le 1.27) \\ 3.6A_s\sqrt{h_{as}} & (1.27 \le A_a/A_s) \end{cases} \qquad 3□$$

where,

$$□ z_{avg} = \frac{\sum_k z_k B_{op,k} H_{op,k}}{\sum_k B_{op,k} H_{op,k}} \qquad 4□$$

$$\square A_a = \sum_k A_{a,k}, \square A_s = \sum_k A_{s,k} \qquad 5\square$$

$$\square h_{as} = \left(\frac{\sum_k A_{s,k} \sqrt{h_{s,k}}}{\sum_k A_{s,k}} \right)^2 + \left(\frac{\sum_k A_{a,k} \sqrt{h_{a,k}}}{\sum_k A_{a,k}} \right)^2 \qquad 6\square$$

3 Combustion Controlled Parameter

Combustion controlled parameter means regnant factor of fire behavior and separates in two regimes, i.e., the ventilation controlled stage and the fuel controlled stage. Fire behavior depends on fuel conditions and opening conditions, namely the fuel surface area and the ventilation parameter, respectively. In this evaluation method, the combustion controlled parameter was derived by dividing the ventilation parameter by the fuel surface area.

$$\square \chi = \left(A\sqrt{H}\right)_{eff} \Big/ A_{fuel} \qquad 7\square$$

4 Heat Release Rate

To investigate the effect of the fuel conditions and ventilation parameter on the burning rate, compartment fire experiments were conducted. As a result, the mass burning rate increases proportionally to the ventilation parameter and well agrees with the relationship given by Kawagoe et al. regardless of the type and the surface area of fuels when the ventilation parameter is small. Moreover, the mass burning rate gradually decreases as the ventilation parameter increases beyond a certain value and asymptotically approaches the free burning rate of fuel[4)]. Based on the result, the mass burning rate transformed the heat release rate. It can be expressed as:

$$\square q_b = A_{fuel} \times \begin{cases} 1.6 \times \chi & (\chi \le 0.07) \\ 0.112 & (0.07 < \chi \le 0.1) \square\square \\ 1.92 \times \chi \times \exp(-11 \times \chi) + 0.048 & (0.1 < \chi) \end{cases} \qquad 8)$$

□ Total Heat Release of Fuel

Total heat release of fuel is derived from the sum of live load and dead load that is carried in a compartment. The heat release of live load and dead load can be taken from Table 1 and Table 3, respectively. The value of total heat release is estimated by:

$$\square Q_r = q_l A_{floor} + \sum q_{fix} A_{fix} d_{fix} \qquad 9)$$

Table 3□ Heat release rate per area and thickness of building interior material :□$_{fix}$

Occupancy	HRR q_{fix}□MJ/m^2/cm□
Noncombustible material	8
Fire retardant material□excluding noncombustible material□	16
Slow burning material□excluding noncombustible material and fire retardant material□	32
Material excluding above	80

□ Fire Duration

Fire duration was calculated by dividing by the total heat release by the heat release rate, i.e.:

$$t_f = \frac{Q_r}{60 q_b} \qquad 10)$$

□ Fire Severity Parameter

Fire severity parameter□indicates the inclination of temperature rise within a fire compartment. The greater the value of □, the faster temperature rises. To calculate the fire severity parameter, heat property of fire compartment wall, opening conditions and fuel conditions were taken into consideration. Thus:

$$\square\ \beta = 1280\left(\frac{q_b}{\sqrt{A_T\sqrt{k\rho c}\sqrt{(A\sqrt{H})_{eff}}}}\right)^{2/3} \qquad 11)$$

□ Fire Temperature Curve

Fire temperature curve given by using the fire severity parameter is calculated by the next equation.

$$\square\ T_t = \beta t^{1/6} + T_0 \qquad 12\square$$

As for ISO 834 Standard Fire Temperature Curve(SFTC), the value of □ is approximately 460.

2.2□Structural Stability(under discussion)

1 Critical Temperature of Steel Member

To evaluate structural stability for steel structure buildings, several simplified calculation methods have been developed. Their function is to bridge the gap between element classification according to design plans and elaborate scientific computer models. In present evaluation method, closed-form equations were used to evaluate structural stability. By calculating the steel temperature of a column or beam, it can be determined whether it reaches to the critical temperature or not in a fire, i.e., collapse of most structural components in a fire can be related to the loss of strength at high temperature. The critical temperature of a column or beam is estimated by the next equations.

$$\square\ x(T) = \begin{cases} 1 & : T_R \le T < 300 \\ \dfrac{750 - T}{450} & : 300 \le T < 750 \end{cases} \qquad 13)$$

1) Beam critical mode

$$\overline{q}_A(T) = x(T) \qquad 14)$$

2) Column and beam critical mode

$$\overline{q}_B(T) = x(T)\left\{\frac{1}{2} + \tau\left(\frac{\overline{p}}{x(T)}\right)\overline{Z}\right\} \qquad 15)$$

3) Column critical mode

$$\overline{p} = x(T_c) \qquad 16)$$

where

$$\square\ \overline{q} = \frac{ql^2}{4M_{PB}},\ \overline{Z} = \frac{M_{PO}}{M_{PB}} \qquad 17)\ 18)$$

2 Temperature-time Curve of Steel with Protection Material

If the temperature-time curve for the fire exposure is known, the steel temperature-time of a structural member can be calculated from heat transfer calculations. Thereby, the time until steel achieved critical temperature can be estimated. On the other hand, the critical time can be also evaluated by fire tests. Equations conducted by experiment results obtained from ISO 834 Fire Tests were used in this method.

□ $t_{C,ISO} = a_0\left(\frac{1}{H_{st}/A_{st}} + a_1\right)(d_i + a_2)(T_{C,ISO} + a_3) + a_4$ 19□

a)Rock wool□a_0=0.2331,a_1=0.0096,a_2=13.9764,a_3=404.7274,a_4=-50.2965□($57<H_s/A_s<196$)
b)Calcium silicate board a_0=1.427802,a_1=-0.00095,a_2=-3.41117,a_3=-82.2283,a_4=-28.43666□($57<H_s/A_s<196$)

As the above equations correspond to the ISO 834 SFTC (fire severity parameter□=460), by way of enabling application to different parameter □, the temperature-time curve was derived by below equation[5)].

□ $t_{f,ISO} = 1.2\left(\frac{\beta}{460}\right)^{3/2} t_f$ 20)

2.3□Evaluation of Structural Stability

If critical time of structural member ($t_{C,ISO}$) is longer than fire duration time($t_{f,ISO}$), building structural member may remain stable. Conversely, if critical time of structural member is shorter than fire duration time, modification of insulation etc. is required.

3.CASE-STUDY

In a sense, the calculation methods are intended to give data in order to replace fire test results. As regards evaluation of structural elements, simplified calculation methods are assumed to provide a level of safety equal to or better than prescriptive requirements. However, the safety level of its method is not actually well known. Then, case study using this evaluation method was carried out.

3.1 Conditions

The following types of buildings were used:
a)Apartment house, b)Hotel, c)Office(office room), d)Office(meeting room), e)Retail shopping, f)Hospital(sickroom), g)School, h)Exhibition hall

For calculation purposes, building features, i.e., floor area, height and wall surface area of room, opening width and height etc. were taking from building plans.

3.2 Results

The case study was carried out from about 80 building plans. First, the example of a case study using this evaluation method is shown in detail. The type of building is an office.

3.2.1 Calculation conditions

Figure 1 shows office building plan as the object of the case study and Table 4 indicates the required conditions necessary to calculate by closed-form equations under the building plan.

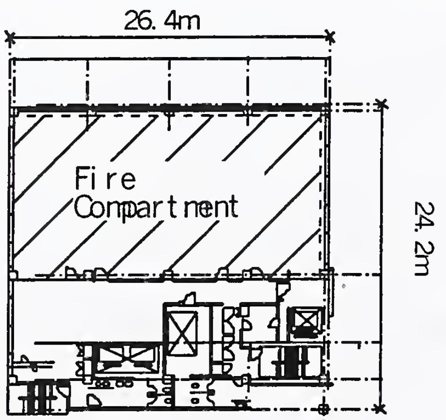


Table 4 Calculation conditions

1) Compartment /Opening etc.

Compartment	Width	26.1m
	Depth	13.9m
	Height	2.7m
	Inside wall area	941.6m²
	Spandrel height	2m
Opening	Width	20m
	Height	1.9m
Fuel Density		35kg/m²
Ambient temperature		293K

Figure 1 Office building plan
Table 4 Calculation conditions
2) Beam/Column

Beam (H-700*250*14*28)	
Sectional area	0.0232 m^2
Plastic section modulus	0.006155 m^3
Section modulus	0.005409 m^3
Moment of second order	0.00189306 m^4
	0.00007306 m^4
Radius of gyration	0.056 m
Width-thickness ratio of flange	4.2
Width-thickness ratio of web	46
Thickness of calcium silicate board	0.03 m

Column (H-600*600*32)	
Sectional area	0.0674 m^2
Plastic section modulus	0.015502 m^3
Section modulus	0.013073 m^3
Moment of second order	0.00392175 m^4
Radius of gyration	0.232 m
Width-thickness ratio of flange	18.8
Compartment height	3.9 m
Slenderness ratio	16.8
Thickness of calcium silicate board	0.03 m

□

3.2.2 Fire room temperature and fire duration time

The temperature-time curve in fire compartment can be simulated by closed-form equation. Figure 2 and Table 5 indicate results comparing prediction result with ISO 834 SFTC on fire duration time and peak of temperature.

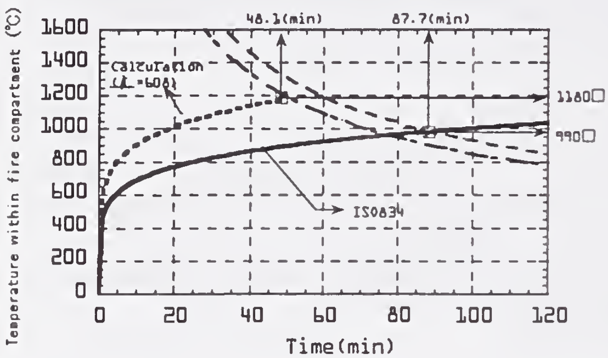


Figure 2 Temperature-time curve

Table 5 Fire duration time and fire maximum temperature

Fire duration time(t_f)	48.1min
Fire maximum temperature($T_{t,max}$)	1180□
Fire duration time by ISO834($t_{□,ISO}$)	87.7min
Fire maximum temperature by ISO834($T_{t,max,ISO}$)	990□

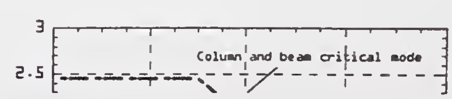
As can be seen in Figure 2, the temperature rise predicted by closed-form equations is higher than the ISO 834 Standard Fire Temperature Curve. In short, fire severity parameter □ is larger than ISO 834.

3.2.3 Structural stability

The structural stability of steel structure buildings was estimated by closed-form equations based on 'Simple Plasticity Theory'. By using these equations, it was possible to evaluate the temperature of steel columns and/or beams, and whether it would reach to the critical temperature or not.

Figure 3 shows steel temperature-time curves of a column and a beam, respectively. From the calculation result given in Figure 3, maximum temperature of the column and the beam is 195 □ and 414 □, respectively.

Using maximum steel temperature of column and beam, structural stability can be estimated as



shown in Figure 4. Consequently, it is found that steel structures stabilize against fire from estimation of this case study.

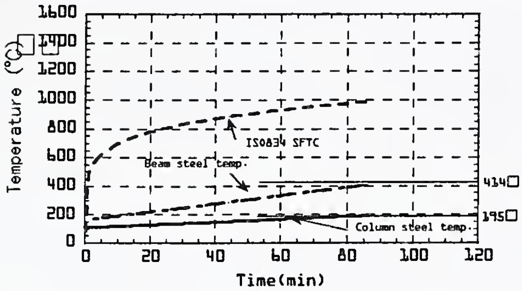


Figure 3 Calculation result of steel temperature of column and beam

4.CONCLUSION

In this report, the evaluation method composed of closed-form equations and results of case-study by its method was indicated. The case study shown in this report only exemplifies rigid frame structure type. It is necessary to carry out further case studies about other structure types.

SYMBOL

A: opening area (m^2), A_a: lower opening area(m^2), A_{fix} surface area of building interior material(m^2), A_{fuel}: fuel surface area(m^2), A_{floor} floor area (m^2), A_s: upper opening area(m^2), A_{st}: cross section area of steel(m^2), A_T: surface area of compartment inside wall (m^2), B_{op}: opening width(m), c: specific heat(kJ/kgK), d_i thickness of insulation(mm), d_{fix} thickness of building interior material(m), H: opening height(m), H_a: lower opening height(m), H_{op}: opening height(m), H_s: upper opening height(m), H_{st}: perimeter length of steel(m), k: heat conductivity(kW/mK), q_{fix} heat release rate per unit area and unit thickness of building interior material ($MJ/m^2/cm$), q_l heat release rate per unit surface area of live load(MJ/m^2), t time after fire occurrence(min), $t_{C,ISO}$ critical time of steel heated by ISO834 standard fire curve min, $T_{C,ISO}$ critical temperature of steel(), T_0: ambient temperature(=20)() , : density(kg/m^3)

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A RISK-BASED TRANSLATION OF FIRE RESISTANCE REQUIREMENT

Takeyoshi TANAKA
DPRI, Kyoto University

Yoshifumi OHMIYA
Building Research Institute, MOC

INTRODUCTION

It is quite common in fire safety codes of buildings that the higher or the larger the building, and the larger the number of occupants, the more strict the provisions applied. This, of course, intends to reduce the probability and the potential size of fire loss. Although the consistency of the principle and the attainable level of the prescriptive provisions of the existing codes is questionable, the favorable interpretation of their intention will be expressed in a scientific term as "to control fire risk under a certain level", that is, letting R be the fire risk, P_L be the probability of fire loss occurrence, S_L be the potential size of the loss, and R_a be the acceptable fire risk,

$$R = P_L S_L \leq R_a \tag{1}$$

By so considering, many provisions can be interpreted in a rational manner. For example, the fire resistance requirements on principal structural members intends to control the fire risk by lowering P_L; compartmentation and shaft sealing by limiting S_L as well as to lowering P_L; provisions for safe escape routes are not imposed, or at least very lightly if any, for small buildings such as family dwellings because the potential size of life is so small.

Currently, attempts are being made for developing performance-based fire safety design systems in many countries[1]. It will be important to reflect the fire risk concept, which obviously exists in the current codes albeit implicitly, on the new performance-based system for its rational structuring. In

this paper, conversion of the fire resistance requirements in the Building Standard Law to a risk-based performance-based standard is discussed.

1. PERFORMANCE-BASED STANDARDS AND ACCEPTANCE OF FIRE RISK

It is becoming to be a common understanding that a performance-based standard is given in terms of a design fire and a safety criterion. The design fire will be standardized as the fire whose heat release rate $\dot{Q}$ initially grows proportionally to square of time t, i.e. $\dot{Q} = \alpha t^2$, and later on stays constant at maximum value controlled by ventilation condition etc., as illustrated in FIGURE 1. The duration of the maximum heat release period is approximately proportional to fire load, hence to fire load density w in a specific fire compartment.

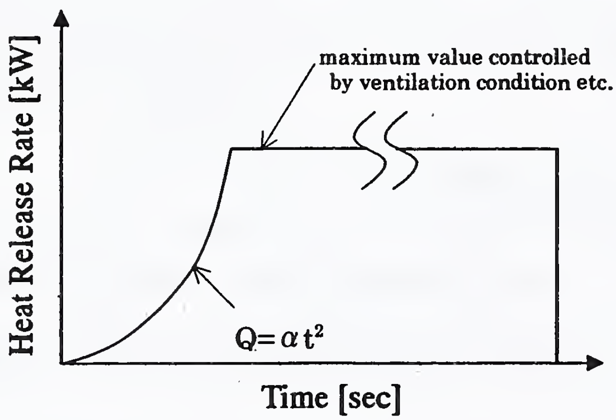
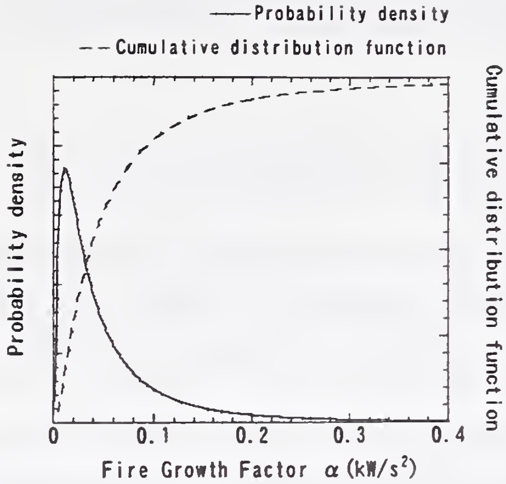
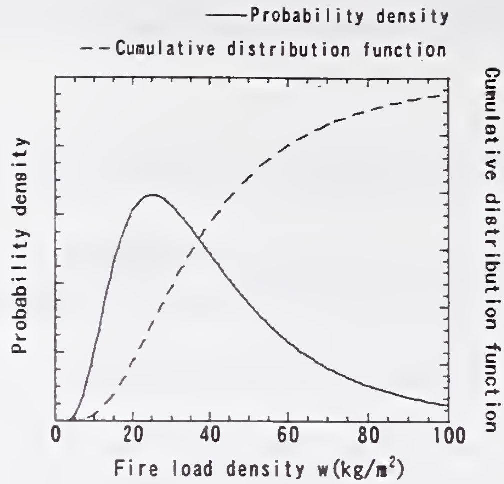


FIGURE 1 Design Fire in a Performance-based Design System

The fire growth factor α [kW/s²] affects the smoke filling in the early stage of fire, hence important for the assessment of evacuation safety and the fire load density w [kg/m²] is related to fire duration, so important for the evaluation of structural stability of load bearing members and prevention of fire spread by fire walls. Both of these are not fixed values but vary as are illustrated in FIGURE 2 by the conceptual probability density distribution. Therefore, it is necessary to choose a certain appropriate value as the standard for designs taking to specifically determine a design fire. Once the design fire is defined, measures will be taken so as to assure the safety of a building under this premise. If the conditions of a fire occurred happens to be severer than those of the design fire the safety measures may fail. Generally speaking, the higher the standard values, the lower the failure probability is supposed to be but the higher the cost of the safety measures will be at the same time, therefore a compromise is necessary. Deciding the standard values implies the acceptance of a certain level of fire risk.



(a) Fire growth factor α



(b) Fire load density w

FIGURE 2 Conceptual Probability Distribution of α and w

2. FIRE RISK RELATED TO FULLY DEVELOPED FIRE

It is considered to be rational to determine the values of α and w, which specify the design fire, based on the acceptable fire risk, however, their probability distributions are needed to do so. In this paper, only the fire risk in which fire load density is involved since an extent of the statistical data are available based on field fire load survey.

2.1 Acceptable Failure Probability

The fire in which fire load density becomes to be an issue is such a fire that whole combustibles in the room are involved in the fire, in other words, a fully developed fire. Structural stability and integrity of compartment wall and so forth are discussed usually assuming fully developed conditions of fire. In this case, it is when a fire breaks out, it grows to be a fully developed fire, fire brigades fail to suppress it and the measures to cope with the fire fails that the fire loss occurs. Hence the fire loss occurrence P_L in Eqn.(1) can be written as

$$P_L = P_{fire} P_{FO} P_{\sup} P_{fail} \tag{2}$$

where P_{fire}s the fire occurrence probability, P_{FO} is the probability that a fire grows to be a fully developed fire, P_{sup} is the probability that fire brigades fail to suppress the fully developed fire and P_{fail} is the failure probability of the safety measure.

Note that in the performance-based standard where a standard value of fire load density w_0 is given the maximum value of P_{fail}, i.e. the acceptable failure probability, is the same as the probability that fire load density exceeds the standard value w_0.

2.2 Examples of Fire Risks Related to Fully Developed Fire

(1) Fire wall performance

The example illustrated in FIGIRE 3 denotes two rooms, room 1 and room 2, separated by a fire wall with a certain level of performance to prevent fire spread across the wall. In other words, this wall can prevent fire spread provided that fire load density does not exceed a certain standard value of fire load w_0. Let A_1 and A_2 be the floor areas of room1 and room 2, respectively.

Considering that the fire occurrence probability in room 1 is proportional to the area and the life time, the probability $P_{1,fire}$ is expressed as

$$P_{1,fire} = p_f A_1 Y_L \tag{3}$$

where p_f is the fire occurrence probability per unit area and per year and Y_L is the life year of the room.

Further letting q be the value of room 2 per unit area, the fire risk of room 2 due to the fire from room 1 R_{12} is given as

$$R_{12} = \left(p_f A_1 Y_L\right) P_{FO} P_{\sup} P_{fail} \left(q A_2\right) \tag{4}$$

Hence, if the acceptable fire risk should be the same regardless the areas of the rooms, the failure probability of the fire wall P_{fail} needs to be

$$P_{fail} \le \frac{R_a}{p_f P_{FO} q P_{\sup} Y_L A_1 A_2} \tag{5}$$

Incidentally, the fire risk of room 1 due to the fire in room R_{21} becomes the same as Eqn.(5) if the conditions of the two rooms are identical, i.e. p_f, P_{FO}, P_{sup}, Y_L and q are the same. In other words, the performance of the fire wall can be the same against the heat exposure from either surface.

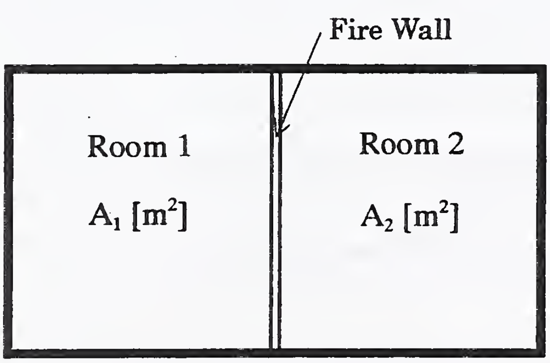


FIGURE 3 Two Rooms Separated by a Fire Wall with a Certain Level of Fire Stop Performance

(2) Stability of structural members

Here we discuss the issue of fire resistance requirements with building height. A multiple story

building having the same floor area A_{FLR} on every story, as illustrated in FIGURE 4 is considered for simplicity.

It is assumed here that all the floors above the fire floor have to be abandoned if a principal structural member on the fire floor collapsed, although there may be a room for dispute on this point. Then, letting N be the number of floors above the fire floor, the fire risk due to the fire R_N can be given as

$$R_N = \left(p_f A_{FLR} Y_L\right) P_{FO} P_{\sup} P_{fail} \left(N q A_{FLR}\right) \tag{6}$$

Since R_N must be smaller than the acceptable fire risk R_a, the failure probability of the structural member needs to be

$$P_{fail} \leq \frac{R_a}{p_f P_{FO} P_{\sup} q Y_L N A_{FLR}^2} \tag{7}$$

that is, the failure probability of the structural member on a floor should be inversely proportional to the number of floors above the floors and the square of the floor area.

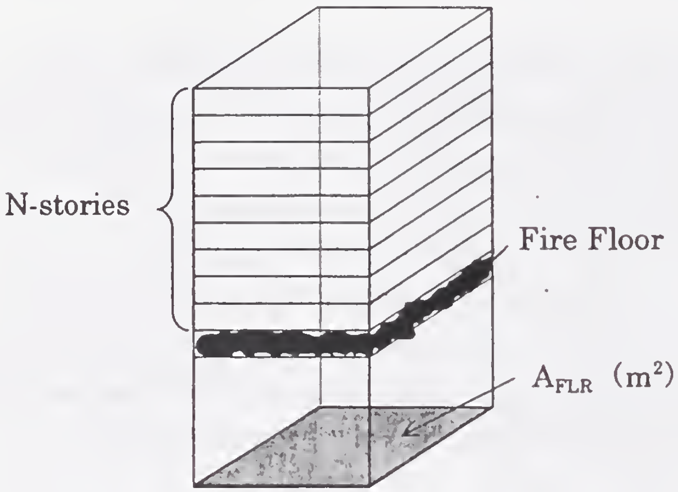


FIGURE 4 A Multiple Story Building with a Certain Level of Fire Resistance

3. CONVERSION OF REQUIRED FIRE RESISTANCE TIME TO FIRE LOAD DENSITY

3.1 Acceptable Structural Failure Probability as a Function of Building Condition

The discussion here is focused on the structural stability, although similar arguments may be possible regarding the fire wall performance.

If it is allowed to insist that the acceptable failure probability of structures should be the same regardless the number of floors above the fire floor and the floor area, the following relationship holds between two arbitrary buildings:

$$p_f P_{FO} P_{\sup} q Y_L N A_{FLR}^2\} P_{fail} = \overline{p_f P_{FO} P_{\sup} q Y_L N A_{FLR}^2\}} \overline{P_{fail}} \qquad (8)$$

hence

$$P_{fail} = \left(\frac{\overline{p_f}}{p_f}\right)\left(\frac{\overline{P_{FO}}}{P_{FO}}\right)\left(\frac{\overline{P_{\sup}}}{P_{\sup}}\right)\left(\frac{\overline{q}}{q}\right)\left(\frac{\overline{Y_L}}{Y_L}\right)\left(\frac{\overline{N}}{N}\right)\left(\frac{\overline{A_{FLR}}}{A_{FLR}}\right)^2 \overline{P_{fail}} \qquad (9)$$

Therefore, if the conditions in the right hand side of Eqn.(8) can be specified by choosing a reference building, the acceptable failure probability of an arbitrary building P_{fail} can be determined from Eqn.(9) as a function of the conditions of the building. Naturally, such a reference building should be selected from the buildings for which fire resistance time is prescribed in the existing codes. The Building Standards Law, Japan, requires fire resistance time from 1 hour to 3 hours according to the number of stories, but virtually no indications on the other conditions such as those exhibited by the parameters in Eqn.(9), except the number of stories N. Therefore, several conditions of the reference building need be presumed taking into account the actual state of buildings. However, as is suggested by Eqn.(9), it is not always necessary to know the absolute values of these parameters but enough to know the values relative to the reference conditions. If there is no solid reason to make difference, it may be allowed to assume

$$\left(\frac{\overline{p_f}}{p_f}\right)=1,\quad \left(\frac{\overline{P_{FO}}}{P_{FO}}\right)=1,\quad \left(\frac{\overline{P_{\sup}}}{P_{\sup}}\right)=1,\quad \left(\frac{\overline{q}}{q}\right)=1,\quad \left(\frac{\overline{Y_L}}{Y_L}\right)=1 \qquad (10)$$

until some facts have been found regarding these parameters.

Incidentally, it has been reported from fire incidence statistics that the probability of flashover of sprinklered rooms is 1/4 - 1/5 of that of unsprinklered rooms[2]. Therefore, if a room happens to be sprinklered, it may be appropriate to estimate as $\overline{P_{FO}} / P_{FO} = 4 - 5$.

3.2 Acceptable Failure Probability for Reference Condition ($\overline{P_{fail}}$)

(1) Fire load density and fire duration

Although it is rational to consider that structural failure probability is the probability that fire load density exceeds the standard value of the density, the structural failure criteria in the existing codes are prescribed in terms of fire duration. Accordingly, the presumption of the acceptable failure probability for reference condition has to begin with the relationship between the fire load density and the fire resistance time.

Usually, the duration of a fully developed fire t_D is assessed as follows

$$t_D = \frac{W}{m_b} = \frac{wA_{FLR}}{0.1A_W\sqrt{H_W}} \qquad (11)$$

where W and m_b are the total fire load and the burning rate, respectively, and $A_W\sqrt{H_W}$ is the ventilation factor of the compartment.

Eqn.(11) can be rewritten as

$$t_D = \Omega \cdot w \qquad (12)$$

where Ω is the coefficient defined by

$$\Omega \equiv \frac{A_{FLR}}{0.1A_W\sqrt{H_W}} = 10\left(\frac{A_T}{A_W\sqrt{H_W}}\right)\left(\frac{A_{FLR}}{A_T}\right) \qquad (13)$$

where A_T is the total boundary surface area of the compartment.

The values in the two ( )s in Eqn.(13) , i.e. the so-called temperature factor and the ratio of the floor area to the total surface area, respectively, depend on the design of the space and affect on the temperature and the duration of the fire. The Building Standards Law do not explicitly describe anything on such conditions of buildings but simply states that the required fire resistance time is the tome until which the structural member has to endure against the exposure to the "usual fire". The "usual fire" considered in the Law seems to be nothing but the fire resistance test condition prescribed in JIS 1304. In this test, the temperature rises to 925℃, hence about 900℃ rise from from room temperature.

On the other hand, it is known that the temperature rise of fully developed compartment fires can be given as[3], [4]

$$\frac{\Delta T_F}{T_\infty} = 3.0\left(\frac{A_W\sqrt{H_W}}{A_T}\right)^{1/3}\left(\frac{t}{k\rho c}\right)^{1/3} \qquad (14)$$

The dependence of the temperature rise in fire resistance tests is known to be close to that of this equation. It is clear that the fire temperature rise depends on thermal properties of boundary wall as well as temperature factor of a compartment. Assuming that normal concrete are considered as the typical wall material in building codes, $t/k\rho c \approx 0.3t$ is used in Eqn.(14). Substituting the temperature rise condition of the above mentioned JIS 1304 fire test, the temperature factor corresponding to the fire resistance tests can be obtained as

$$\frac{A_W\sqrt{H_W}}{A_T} \approx \left(\frac{\Delta T_F/T_\infty}{3.0}\right)^3\frac{1}{(0.3t)^{1/2}} \approx \left(\frac{900/300}{3.0}\right)^3\frac{1}{(0.3\times 3600)^{1/2}} \approx \frac{1}{33} \approx 0.03 \qquad (15)$$

that is, what the Building Standards Law call "usual fire" is interpreted as the fires in the rooms whose temperature factor is around 0.03, which is well in a realistic range of its values of actual buildings.

The value of another factor in Eqn.(13), i.e. the ratio of floor area to total boundary surface area A_{FLR}/A_T varies with the size of rooms. However, the estimation of the values for the rooms having

3m of the ceiling height and the floor area of 100 - 1500 m^2 reveals that this value is roughly in the relatively narrow range as follows

$$\frac{A_{FLR}}{A_t} = 0.3 - 0.42 \tag{16}$$

Although the exact room conditions considered in the building code is not clear, the average value is simply employed here. Then the value of Ω in Eqn.(12) is estimated as

$$\Omega = 10 \times 33 \times 0.36 \approx 119 \tag{17}$$

(2) Probability density distribution of fire duration

The fire load density w varies considerably depending on the manner of use of rooms. Its probability density distribution might be regard as a normal (Gausian) distribution, but here it is assumed that it is a log-normal distribution, that is, ln w follows the normal distribution $[\mu_{\ln w}, \sigma_{\ln w}]$ defined as follows[5], [6]:

$$\psi(\ln w) = \frac{1}{\sqrt{2\pi}\sigma_{\ln w}} \exp\left\{ -\frac{(\ln w - \mu_{\ln w})^2}{2\sigma_{\ln w}^2} \right\} \tag{18}$$

In this equation, letting μ_w and σ_w be the mean and standard deviation of fire load density w, $\mu_{\ln w}$ and $\sigma_{\ln w}$ in Eqn.(18) are given as follows:

$$\mu_{\ln w} = \ln\left\{\mu_w / \sqrt{1 + (\sigma_w / \mu_w)^2}\right\} \tag{18-2}$$

$$\sigma_{\ln w} = \sqrt{\ln\left\{1 + (\sigma_w / \mu_w)^2\right\}} \tag{18-3}$$

Noting that taking logarithm of Eqn.(13) yields

$$\ln t_D = \ln \Omega + \ln w (\approx 4.78 + \ln w) \tag{19}$$

it is obvious that ln t_D follows to the distribution of Eqn.(18) shifted to the right by $\ln \Omega$, i.e. the normal distribution $[\mu_{\ln w} + \ln \Omega, \sigma_{\ln w}] \equiv [\mu_{\ln t_D}, \sigma_{\ln t_D}]$. Incidentally, the standard deviation of the distribution of ln t_D is the same as that of ln w. Further, by normalizing the fire duration t_D as

$$\tau = \frac{\ln t_D - \mu_{\ln t_D}}{\sigma_{\ln t_D}} \tag{20}$$

τ follows the standard normal distribution [0,1], that is

$$\phi(\tau) \equiv \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\tau^2}{2}\right) \tag{21}$$

(3) Calculation of the failure probability

It is clear from the above discussion that if fire load density follows a log-normal distribution and if structural members collapse when fire duration exceeds the prescribed fire resistance time t_X, the failure probability of the structural members can be obtained by following the procedure (i) -(iii) as

shown in the below:

(i) The mean $\mu_{\ln t_D}$ and the standard deviation $\sigma_{\ln t_D}$ of log-normal distribution of fire duration

Letting μ_w and σ_w be the mean and the standard deviation of fire load density w,

$$\mu_{\ln t_D}\left(=\mu_{\ln w}+\ln\Omega\right)=\ln\frac{\mu_w}{\sqrt{1+\left(\dfrac{\sigma_w}{\mu_w}\right)^2}}+\ln\Omega \tag{22}$$

$$\sigma_{\ln t_D}\left(=\sigma_{\ln w}\right)=\sqrt{\ln\left\{1+\left(\frac{\sigma_w}{\mu_w}\right)^2\right\}} \tag{23}$$

(ii) The normalized fire resistance time t_X

Using $\mu_{\ln t_D}$ and $\sigma_{\ln t_D}$ calculated in the above, and letting t_X be the prescribed fire resistance time,

$$\tau_X=\frac{\ln t_X-\mu_{\ln t_D}}{\sigma_{\ln t_D}} \tag{24}$$

(iii) The failure probability of the structural member $\overline{P_{fail}(t_X)}$

Letting t_X be the prescribed fire resistance time, the failure probability $\overline{P_{fail}(t_X)}$ is given as

$$\overline{P_{fail}(t_X)}=\int_{\tau_X}^{\infty}\phi(\tau)d\tau\{\equiv\Phi(\tau_X)\} \tag{25}$$

(4) The failure probability for the prescribed fire resistance time

According to the above described procedure, attempts were made to seek for the failure probability for the fire resistance time prescribed in the Building Standard Law. Two cases were considered regarding the mean and the standard deviation of the fire load density, i.e., (μ_w =30, σ_w =10) and (μ_w=40, σ_w =20). These values are not exactly based on the existing fire load survey but not unrealistically far from the survey data for office buildings[7]. The calculated results of the failure probability estimated for 1, 2 and 3 hours of fire resistance rating are shown in TABLE 1.

According to TABLE 1, the failure probability for one and two hour rated structures are considerably high, despite that we hardly encounter the collapse of the buildings to which such requirements are imposed. The primary cause is considered to be the combination of the factors as follows although many other may be conceivable.

(a) Significant safety allowance is involved in the specifications and the fire resistance test criteria for one and two hour rated structures.

(b) Even though the failure probability is high, the probability of actual collapse, which is the product of several probabilities indicated in Eqn.(2), is low enough so that the collapse of buildings does not take place as frequent as to be perceived in everyday life. Particularly, fires are

extinguished well before all the combustibles have been consumed thanks to the intervention of fire brigades.

(c) In structural designs of buildings, safety factors are considered in both the design load and the safety criteria for structural materials. As a result, the structural members are far less loaded than their loading capacity.

TABLE 1 The Failure Probability of Structures Rated to 1, 2 and 3 Hours Fire Resistance

	μ_w=30, σ_w=10	μ_w=40, σ_w=20
P_{fail}(1h=3600)	0.43	0.64
P_{fail}(2h=7200)	0.01	0.13
P_{fail}(3h=10800)	0.0002	0.02

As for cause (c), FIGURE 5 shows the results of the survey conducted by Building Contractor's Society of Japan for the ratio of the loading in the designs to the allowable loading to steel columns of the buildings[8]. According to FIGURE 5, the most frequent loading ratio is only 0.2 and more than 95% of columns are covered in the range less than 0.4. As shown in TABLE 2, the failure probabilities for structures with such small loading ratio are extremely low.

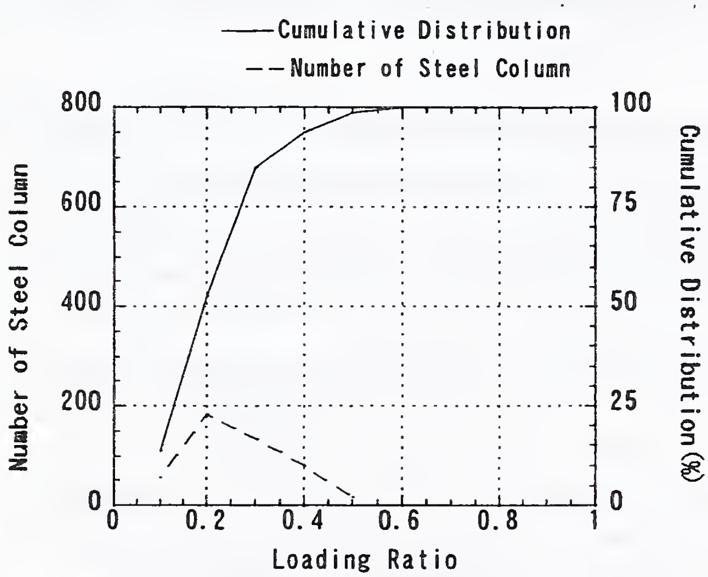


FIGURE 5 The Loading Ratio in the Structural Designs of Steel Columns

TABLE 2 The Failure Probability of the Structures with Different Loading Ratios

Roading Ratio	μ_w=30, σ_w=10	μ_w=40, σ_w=20
0.2	4.52×10^{-8}	7.15×10^{-4}
0.4	2.31×10^{-7}	1.44×10^{-3}
0.6	7.12×10^{-7}	2.34×10^{-3}
0.8	2.28×10^{-6}	3.84×10^{-3}
1	1.39×10^{-5}	8.30×10^{-3}

3.3 Fire Resistance Requirement Based on Acceptable Failure Probability

In view of controlling the fire risk of buildings under an acceptable level, it is most rational to determine the design fire load density corresponding to the acceptable failure probability, taking into account the various factors suggested in Eqn.(9), and to provide necessary safety measures based on the prediction of fire behavior under the design fire load density.

(1) Code equivalent performance-based fire resistance standard

The failure probability of the structures complying to the current provisions are not necessarily low as seen in the above. However, considering that the collapses of buildings are rare thanks to the many other factors involved, the probability can be said appropriate as the acceptable failure probability under the condition at which such factors are disregarded.

In the current Building Standards Law, there is as large as one-hour gap between 4 and 5 story, and between 14 and 15 story. However, the acceptable failure probability of structures should change continuously with number of story from the viewpoint of the fire risk expressed by Eqn.(9). In order to use Eqn.(9) to determine the acceptable failure probability of arbitrary buildings, it is sufficient to define only one reference building. FIGURE 6 demonstrates how the acceptable failure probabilities change with number of stories when a building with 5, 10 and 14 stories, which are in the range of two-hour fire resistance rating in the code, are selected as the candidates of the reference buildings. It was assumed that the area of a floor of the reference building is the same within this range of stories so number of stories is the only variable. The reason that the candidate reference buildings are selected only in this range of floor is that the fire resistance requirements for 4-stories or less is somewhat complicated and that there is no height limit for 15-stories or more in the code, hence it is difficult to specify the number of stories of the reference building.

The acceptable failure probabilities based on Eqn.(9) and the reference buildings can be compared with those based on fire resistance requirements. Needless to say, it is unavoidable that there is some difference between the failure probabilities based on the present method and the building code. However, some of the difference may be justified: According to the present method, the failure probability for low rise buildings is significantly high, but this correspond to that there is little fire resistance requirements for low-rise small buildings in the code as well, so accordingly

they are not expected to endure severe fires; Where the number of stories is high, the failure probability for the code is lower than the acceptable failure probability based on the present method, but this can be explained from Eqn.(9) if higher buildings tend to have larger floor area.

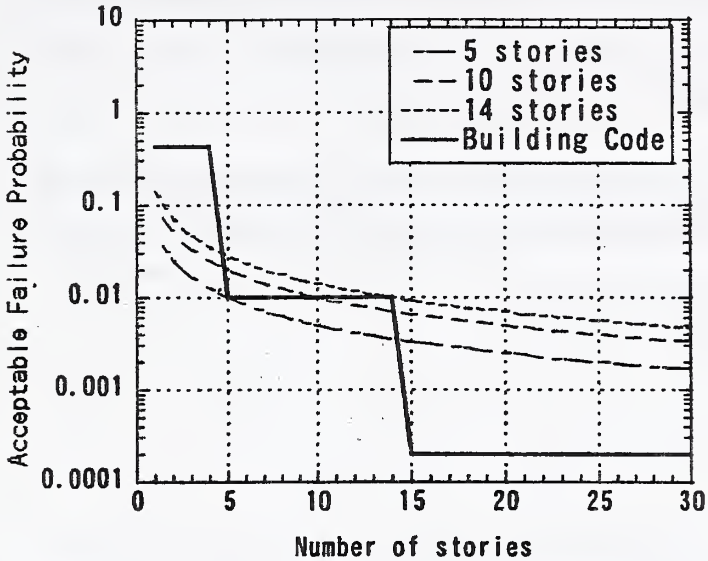


FIGURE 6 The Acceptable Failure Probability with Number of Stories

(2) Determination of design fire load density

As discussed in the above, once the reference building is specified along with its acceptable failure probability, the acceptable failure probability P_{fail} for an arbitrary building can be readily calculated from Eqn.(9) as a function of various conditions of the building. The probability P_{fail} can be converted to the design fire load density for use in the fire safety design as follows:

The normalized fire duration τ_X for P_{fail} can be obtained from Eqn.(25) as

$$\tau_X = \Phi^{-1}(P_{fail}) \tag{26}$$

then, the fire duration t_X can be obtained from Eqn.(24) as

$$\ln t_X = \mu_{\ln t_D} + \Phi^{-1}(P_{fail})\sigma_{\ln t_D} \tag{27}$$

Using Eqns.(22) and (23) to Eqn.(27) to yield more explicit form of t_X

$$t_X = \frac{\mu_w \Omega}{\sqrt{1+\left(\frac{\sigma_w}{\mu_w}\right)^2}} \exp\left[\Phi^{-1}(P_{fail})\sqrt{\ln\left\{1+\left(\frac{\sigma_w}{\mu_w}\right)^2\right\}}\right] \tag{28}$$

Hence, further using Eqn.(13) yields

$$w_X = \frac{t_X}{\Omega} = \frac{\mu_w}{\sqrt{1+\left(\frac{\sigma_w}{\mu_w}\right)^2}} \exp\left[\Phi^{-1}\left(P_{fail}\right)\sqrt{\ln\left\{1+\left(\frac{\sigma_w}{\mu_w}\right)^2\right\}}\right] \tag{29}$$

That is, the design fire load density can be determined only from the mean and the standard deviation of fire load density, i.e. μ_w and σ_w, and the acceptable failure probability P_{fail}, indifferent of Ω, i.e., the ventilation factor and the floor area.

It should be noted that the values of μ_w and σ_w in Eqn.(29) are different from those used to estimate the failure probability of the reference building. These values usually differ depending on the type of use of the space, so the smaller the fire load density, the smaller the design fire load density can be even though the acceptable failure probability P_{fail} is the same.

CONCLUDING REMARKS

Fire behavior heavily depends on the various conditions of the space and the fire load, hence the impact of fire to a building differ from one building to another. Evidently, it is irrational to impose the same fire safety provisions neglecting such difference in building conditions. This is the very reason that attempts are being made worldwide for developing a performance-based design system, in which the safety measures are provided based on the prediction of fire behavior under a certain design fire condition. However, the fire growth factor α and the fire load density w, which constitute the design fires, vary in a wide range so choice of the values for design remains to be an important issue.

On the other hand, it is apparent that the fire safety provisions in the current building codes have been made taking into the fire risk, albeit empirically. In fact, the control of fire risk is considered to be the very essence of the fire safety provisions. In this paper, particularly focusing on the issue of structural fire resistance requirements, an idea to determine the design fire load density at such a value as to make the acceptable fire risk constant for any building. If a different measure of fire loss is considered the conclusion may be slightly different but it seem to be clear that some sort of principle is necessary to define the design fires in a performance-based design system.

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Development of a Hazard-Based Method for Evaluating the Fire Safety of Passenger Trains

Richard W. Bukowski, Richard D. Peacock, Paul A. Reneke, and Jason D. Averill
NIST Building and Fire Research Laboratory
Gaithersburg, MD 20899 USA

Stephanie H. Markos
Volpe National Transportation Systems Center
U.S. Department of Transportation
Cambridge, MA 02142 USA

Abstract

The fire safety of U.S. passenger rail trains currently is addressed through small-scale flammability and smoke emission tests and performance criteria promulgated by the Federal Railroad Administration (FRA). The FRA approach relies heavily on test methods applied to the primary combustible materials of rail car components. As building fire safety regulations move toward performance codes, there has been interest in the application of fire hazard assessment to rail cars using modeling techniques. Accordingly, with FRA funding, the National Institute of Standards and Technology (NIST) and the Volpe National Transportation Systems Center (Volpe Center) have been working on such an alternative approach. This effort included a systematic study of the fire performance characteristics of current rail car materials. First, the heat release and smoke production of actual materials in use were characterized in the Cone Calorimeter. Next, full-scale assembly tests of components such as seats and interior panels constructed of these same materials were conducted in a furniture calorimeter. Finally, full-scale tests of passenger rail cars incorporating the tested components were conducted. The predictive accuracy of fire hazard modeling techniques was assessed against the full-scale test results and the model's utility in evaluating alternative fire safety improvements, such as automatic suppression or smoke exhaust will be demonstrated. The paper provides an overview of six years of work and the findings to date. It is expected that this work could lead to the recognition of fire hazard-based methods as an alternative to the current prescriptive requirements.

CURRENT FRA REQUIREMENTS

As part of the passenger rail equipment rulemaking process required by Congress, the FRA has published requirements that passenger train materials meet certain flammability and smoke emission test methods and performance criteria[1]. These requirements are based on guidelines for intercity and commuter rail cars which FRA first issued in 1984 and revised in 1989 [2,3]. The 1984 FRA guidelines were identical to Urban Mass Transportation Administration (UMTA), now Federal Transit Administration (FTA) recommended practices for rail transit vehicles, also issued in 1984 [4]. The FRA issued revised guidelines in 1989 that used terms and categories to more closely reflect passenger train design and furnishings; smoke emission performance criteria for floor coverings and elastomers were also included.

Based primarily on small-scale test methods which demonstrate fire characteristics of individual materials, the FRA requirements form a prescriptive set of design specifications which historically have been used to evaluate rail car material fire performance. This approach provides a screening

device to allow interested parties to identify particularly hazardous materials and to select preferred combinations of individual components; material suppliers can independently evaluate the fire safety performance of their own materials.

TYPICAL RAIL CAR MATERIALS

Passenger rail cars are constructed primarily of stainless steel; some newer designs incorporate aluminum components. Due to the typically longer distances traveled, the furnishing of conventional passenger train cars is more complex than the furnishing provided in a rail transit vehicle (e.g., subway, light rail). Most intercity and many commuter rail cars are equipped with upholstered seats. Multilevel cars have stairways which allow passengers to move from one level to another. Intercity passenger trains may consist of coach cars, cafe/lounge cars, dining cars, and sleeping cars. In addition, cooking equipment, heat and air conditioning systems, AC and DC power equipment, and lavatories are included in various passenger car designs.

Intercity passenger rail cars typically have interior walls, ceilings, and floors partially covered with carpeting or fabric glued to a perforated sheet metal base material. The underside of the overhead luggage storage rack is covered either with the same carpeting or rigid PVC/acrylic. In some configurations, the carpeting on walls has been replaced with fiberglass-reinforced polymer (FRP) material. Polycarbonate windows are usually used. Fabric drapes are used at windows in many cars. Elastomeric materials are used for gasketing at door edges, around windows and between cars. Polymeric materials are also used in hidden spaces (nonpassenger-accessible space), such as cable and wiring, pipe wrap, ventilation and air ducting. The majority of rail car floors are constructed of plywood/metal (plymetal panels). Fiberglass insulation is used in the floors, sidewall, end wall, and air ducts in the cars. The floor covering consists of carpet and resilient matting.

Coach cars contain rows of upholstered seats, windows and overhead luggage storage space. Coach seats consist of fabric-covered foam cushions installed on steel seat frames with plastic seat shrouds, back shells, and food trays. Seat support diaphragms provide flexible support for the seat bottom. Certain coaches used for longer distances are equipped with padded arm and leg rests, and foot rests, as well as curtains which cover the windows. The seats in first class sections are similar to coach seats described above but plush fabric upholstery installed over thicker foam cushions provides a higher level of comfort. For trains using a single level car configuration, cafe/lounge car interior furnishings are similar to the coach cars. The cafe/lounge cars have a minimal food service area and reduced seat density and may be equipped with tables. Dining cars contain an extensive separate food preparation area, laminated tables and walls, and vinyl upholstered seats. Dining tables are phenolic laminate over plymetal. Seat assemblies are constructed similar to the coach cars.

Sleeping cars contain a series of individual rooms arranged along a corridor plus luggage storage space. Seat configuration in the individual rooms is somewhat different than coach seat configuration, but comparable materials are used in the seat assemblies. The seats convert to beds with fabric-covered foam mattresses; pillows, cotton sheets, and wool blankets provided. Fabric curtains line the doors to provide privacy. Partitions between sleeping compartments and hallways are constructed of plymetal panels.

Materials selected for evaluation were provided by Amtrak which provides U. S. intercity rail passenger service. The Amtrak fleet consists of several generations of passenger rail cars. These include cars which provide coach or first class seating, food service, or overnight sleeping accommodations. Selected materials reflecting a broad cross section of Amtrak passenger train interior finishing materials (representing the bulk of the fire load found in most passenger rail cars) were tested in the Cone Calorimeter. Table 1 lists the materials selected and tested.

COMPARISON OF CONE CALORIMETER TEST DATA WITH EXISTING FRA TEST DATA

Heat release rate (HRR) and fire hazard analysis are the primary focus of this current study of passenger train fire safety. HRR is the key indicator of real-scale fire performance of a material or construction, including ignition, flammability[5], and smoke emission[6] properties. Accordingly, HRR data are necessary to conduct fire hazard analyses and can also be used to predict real-scale fire behavior. Although passenger rail car materials have historically been tested according to test methods and performance criteria which are not directly related to HRR, there have been very few serious fires involving materials which meet the FRA requirements. In this section, the Cone Calorimeter test data are compared to test data obtained from Amtrak for FRA-cited test methods. Although the primary use of the HRR data is as input to a fire hazard analysis, this comparison is also intended to provide a better understanding of the relationships and limitations of Cone Calorimeter test data relative to FRA-cited test method data. A detailed report is available [7].

FRA-Cited Test Method Data

Several FRA-cited test methods include measures of material flammability in terms of flame spread (ASTM E 162, D 3675, and E 648) or ignition/burn resistance (FAA 25.853 (a) and ASTM C 542). ASTM E 162 and D 3675 measure downward flame spread on a near vertically mounted specimen (the specimen is tilted 30 from the vertical with the bottom of the specimen further away from the radiant panel than the top of the specimen). FAR 25.853 (a) and ASTM C 542 are small burner tests which measure a material's resistance to ignition and burning for a small sample of material. ASTM E 648 measures lateral flame spread on a horizontally-mounted specimen. Since ASTM E 648 was designed to measure fire performance of flooring materials, it is the only test method that attempts to replicate end-use conditions. Material flammability and smoke emission test data were obtained for thirty materials from manufacturers and/or suppliers. Additional data from related studies were also reviewed. Data from these related studies [8, 9, 10] show performance similar to the current tests.

Of the materials currently in use, only the space divider does not meet the FRA flammability performance criterion; as a window glazing, the same material meets the FRA performance criterion. ASTM E 648 was used to evaluate two floor covering materials: nylon carpet and resilient rubber floor mat. The test data indicated that both met the FRA performance criteria. The FAR 25.853 (a) burn length test data available for 4 of the 10 materials indicated they met the FRA performance criteria. Flame time was available for only 3 of the 10 materials which also passed the criterion.

Table 1. Selected Passenger Train Materials Evaluated in the Study

Category	Sample No.*	Material Description (Components)
Seat and Bed Assemblies	1a, 1b, 1c, 1d	Seat cushion, (foam, interliner, fabric/PVC cover)
	2a, 2b, 2c	Seat cushion, (foam, interliner, fabric cover)
	3	Graphite-filled foam
	4	Seat support diaphragm, chloroprene elastomer
	5	Seat support diaphragm, FR cotton muslin
	6	Seat shroud, PVC/acrylic
	7	Armrest pad, coach seat (foam on metal support)
	8	Seat footrest cover, chloroprene elastomer
	9	Seat track cover, chloroprene elastomer
	10a, 10b, 10c	Mattress (foam, interliner, ticking)
	11a, 11b, 11c	Bed pad (foam, interliner, ticking)
Wall and Window Surfaces	12	Wall finishing, wool carpet
	13	Wall finishing, wool fabric
	14	Space divider, polycarbonate
	15	Wall material, FRP/PVC
	16	Wall panel, FRP
	17	Window glazing, polycarbonate
	18	Window mask, FRP
Curtains, Drapes, And Fabrics	19	Privacy door curtain and window drape, wool/nylon
	20	Window drape, polyester
	21	Blanket, wool fabric
	22	Blanket, modacrylic fabric
	23a, 23b	Pillow, cotton fabric/polyester filler
Floor Coverings	24	Carpet, nylon
	25	Rubber mat, styrene butadiene
Misc	26	Cafe/lounge/diner table, phenolic/wood laminate
	27	Air duct, neoprene
	28	Pipe wrap insulation foam
	29	Window gasketing, chloroprene elastomer
	30	Door gasketing, chloroprene elastomer

* – letters indicate individual component materials in an assembly.
Individual component materials are listed in order in parentheses following the material description
Note: All foam except Sample 3 is the identical type

Available ASTM E 662 test data showed that the majority of samples met FRA smoke emission criteria. Exceptions such as seat support diaphragm, armrest pad, footrest pad, seat track cover, window and door gasketing) represent a small portion of the fire load in a typical vehicle interior. Amtrak is currently considering replacement materials with better fire performance.

It is unclear whether the contribution from all these materials would be significant. However, the issue cannot be adequately assessed through small-scale tests alone. Again, part of the purpose of the current research effort to apply fire hazard analysis to passenger trains is to allow quantitative evaluation of the contribution of an individual material or combination of materials to the overall fire hazard in a passenger rail car.

Cone Calorimeter Test Method Data

The individual material data obtained from the Cone Calorimeter tests are shown in table 2. All Cone Calorimeter tests in this study were conducted at a heat flux exposure of 50 kW/m^2. This level represents a severe fire exposure consistent with actual train fire tests. With the high performance typical of currently used materials, flux exposures higher than 50 kW/m^2 are unlikely. A spark ignitor was used to ignite the pyrolysis gases. All specimens were wrapped in aluminum foil on all sides except for the exposed surface. A metal frame was used and where necessary a wire grid was added to prevent expanding samples from entering into the cone heater. Included in table 2 are ignition time, peak HRR, and average specific extinction area (SEA) for the first 180 s of each test. More extensive data are available [7].

Times to ignition varied from 5 s for the cotton interliner used in the seat assemblies to 115 s for the window glazing. In general, seat and bedding materials and curtain and fabric materials exhibited the shortest times to ignition, typical of thin materials. Wall and window surfaces, as well as window and door gaskets, had the longest times to ignition, typical of thicker materials.

Peak HRR varied over an order of magnitude from 65 kW/m^2 for the graphite foam to 745 kW/m^2 for the wall fabric. The majority of the 34 individual sample materials tested had peak HRR between 100 kW/m^2 and 600 kW/m^2:

- 6 materials had peak HRR below 100 kW/m^2 – including all the seat and mattress foams;
- 25 materials had peak HRR between 100 kW/m^2 and 600 kW/m^2; and,
- 3 materials had peak HRR over 600 kW/m^2 – usually thin materials.

Since the seat foam is one of the largest single combustible materials in a rail car, the low HRR results are particularly important.

SEA data showed a larger distribution for the 180 s average, σ (m^2/kg), as compared to the peak HRR. Peak σ varied from 30 m^2/kg for a seating foam to 1400 m^2/kg for a seat support diaphragm and a rubber floor covering material.

Table 2. Cone Calorimeter Test Data for Selected Passenger Rail Car Materials

Sample Number*	Time to Ignition(s)	Peak HRR(kW/m^2)	SEA 180s Average(m^2/kg)
la, lb, lc, ld	14, 5, 11, 7	80, 30, 420, 360	30, 300, 225, 770
2a, 2b, 2c	14, 5, 8	80, 30, 265	30, 300, 400
3	7	65	40
4	31	295	1400
5	7	190	490
6	28	110	490
7	54	610	780
8	45	400	960
9	26	190	1100
10a, 10b, 10c11a, 11b, 11c	9, 5, 7	80, 25, 150	40, 70, 70
12	30	655	510
13	21	745	260
14	105	270	1000
15	23	120	1000
16	18	270	530
17	115	330	1000
18	53	210	n.a.
19	13	310	380
20	20	175	810
21	11	170	560
22	17	18	n.a.
23	24	340	570
24	10	245	350
25	35	300	1400
26	44	250	80
27	30	140	810
28	7	95	700
29	33	210	1100
30	38	200	1200

n.a. = data not available* letters indicate individual component materials in an assembly. Note: All foam except sample 3 is the same type

Several materials showed elevated HRR and smoke values over an extended period of time.

Although the peak HRR of these materials fall into an intermediate range, the extended duration of the HRR curve makes these materials important for study in future fire hazard analysis efforts.

For component assemblies of materials, the time to ignition was controlled by the exposed layer of material. The peak HRR for assemblies was generally between the highest and lowest peak HRR for individual component materials making up the assembly. Smoke data was greatly reduced compared to individual component materials with 180 s average σ varying from 30 m^2/kg for a mattress assembly to 560 m^2/kg for a pillow.

Cone Calorimeter data from the 1984 FRA/Amtrak study [8], 1990 NHTSA school bus study [9], and 1996 MARC rail car study [11] shows material performance similar to the materials tested for this study. In addition, the NHTSA and MARC data includes tests conducted at a range of incident fluxes which showed an expected increase in peak HRR as incident heat flux increased.

Impact of Small-Scale Test Data on Current Passenger Train Design

For the majority of materials, the relative ranking from "best" to "worst" was similar in both test methods. While the materials tested represent a range of those currently used in passenger trains, many other material combinations are possible in actual use. Accordingly, the comparisons are intended only to show that the Cone Calorimeter test method provides an approach to screen passenger rail car interior materials similar to that provided by the FRA-cited test methods. However, new materials and designs are better judged through a systems approach which considers the impact of material and design choices on the overall fire safety of the system. The use of HRR data in a hazard analysis applied to passenger trains could provide such an overall system evaluation.

ASSEMBLY TESTING

The outstanding passenger train fire safety record shows that current requirements have been successful in preventing small ignition sources from causing major fires. To provide data for fire hazard analysis, selected real scale assemblies from Amtrak trains were tested in the furniture calorimeter. All of the assemblies tested were extremely resistant to ignition. The assemblies tested require an initial fire source ranging from 25 kW to 200 kW to ignite. Some of the materials do not contribute to the fire even with these ignition sources.

These tests represent a range of materials used in intercity passenger trains and are consistent with those tested in the Cone Calorimeter. The tests were arranged in six groups:

- Ten trash bag tests, with six taken from an actual Amtrak overnight train and four filled with newspaper to match the HRR of the trash-filled bags with a more repeatable filling, These newspaper-filled trash bags were used as an ignition source for the seating and bedding tests described below.

- Four coach seat assembly tests to study the burning behavior of entire seating assemblies to varying ignition sources. The assemblies were placed next to a noncombustible wall representative of an Amtrak coach car wall and overhead luggage rack.

- Three bedding assembly tests in a compartment sized to be representative of an economy room on an overnight train. Although the construction materials for the bedding assemblies

are similar to the seating assemblies, the geometry of the compartments is significantly different from that in a coach car.

- Four wall and ceiling carpet tests. In some configurations, wall and ceiling carpet comprise a significant fraction of the surface area in a car. The extent to which the carpeting supports the spread of fire is a controlling factor in fire spread from a seat assembly to the upper walls and luggage rack.

- Six window drape and door privacy curtain tests. Like the carpet, drapes and curtains can be a path for fire spread to the upper walls and luggage rack.

- Two window assembly tests, including window glazing and window masks from Amtrak coach cars. The window assemblies comprise a significant fraction of the wall surface area in a car.

Assembly Test Results

Peak HRR values were measured during each of the 29 tests conducted. For the assemblies tested, the peak HRR ranged from 27 kW for a coach seat assembly (including the TB 133 burner) to 918 kW for a sleeping compartment assembly (including both lower and upper berths, bedding, window drapes, and a trash bag ignition source).

Implications of Test Results on Current Passenger Rail Car Design

Clearly, it takes a significant ignition source for any of the items tested to become involved in a fire. All of the assemblies tested were exposed to an initial ignition source ranging from 17 kW to 200 kW. Some of the materials do not contribute to the fire even with these ignition sources. For example, the seat cushions do not produce a significant HRR even with the severity of the near 200 kW newspaper-filled trash bag ignition source. For the seat assemblies, the HRR results largely from burning of carpeting attached to the rear of the assemblies.

Conversely, if a severe ignition source exists, some of the materials can contribute to further fire growth. The wall carpeting and window glazing, though difficult to ignite, produce high HRR values once ignited. This is consistent with earlier NBS real-scale mockup tests conducted on Amtrak coach interior materials [8]. In these earlier tests, the wall covering (carpeting or window mask) adjacent to the seating were seen as important to the growth of fire in the tests. Also like the earlier NBS tests, the effect of geometry can be significant. In the bed tests, the small enclosed geometry of the sleeping compartment allowed a much larger HRR for the bed assembly tests than for the seat assembly tests, even though the materials are similar.

FIRE HAZARD ANALYSIS

Traditionally, techniques for hazard analysis[12] typically involve a four step process for the evaluation of hazard of a product or products in a specific scenario: 1) defining the context, 2) defining the scenario, 3) calculating the hazard, and 4) evaluating the consequences. For the analysis of passenger trains, this process limits the evaluation to the contribution of specific products without providing an overall assessment of the performance of the entire system.

Therefore, the procedure outlined above was extended for this project to better reflect the minimum appropriate performance of the overall system while maintaining an evaluation of a specific design as compared to that required minimum performance level. For such a systems-based analysis, the process is also conducted in four steps:

1) Defining the application,
2) Calculating the fire performance of the application,
3) Defining specific fire scenarios for the application, and
4) Evaluating the suitability of the proposed system design.

Steps 1 and 4 are largely judgmental and depend on the expertise of the user. Step 2, which involves extensive use of computer software, requires considerable expertise in fire safety practice. The heart of fire hazard analysis, Step 2 is a sequence of procedures implemented in computer software to calculate the development of hazardous conditions over time, calculate the time needed by occupants to escape under those conditions, and estimate the resulting effects on the occupants based on tenability criteria. In addition to evaluating the hazard resulting from specific products used in the design, this new procedure used in this report determines the worst case fire which allows the overall system to meet chosen design criteria. Step 3 defines the specific fires which are likely to occur in the application. Step 4 compares the results of Steps 2 and 3, evaluates the appropriateness of the calculations performed, and determines whether the proposed design meets the design goals established in Step 1.

For the analysis, three different passenger car designs were considered: a single level coach car, a bi-level dining car, and a bi-level sleeping car. For each of these designs, data from the small-scale and assembly-scale testing of actual train car materials were used as input to computer fire models which predict the conditions within a train that result from a specified fire. Figure 1 illustrates the results of the analysis for the coach car.

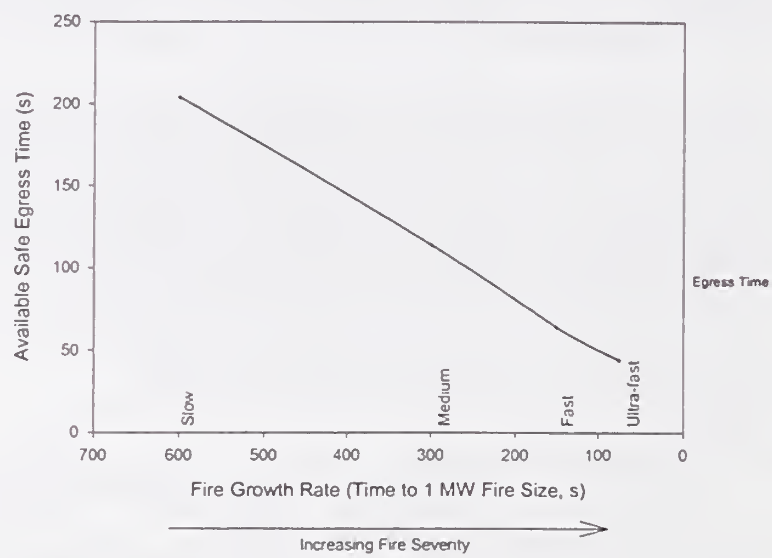

Figure 1 Calculated Fire Performance Graph for Baseline Fire Hazard Analysis of Coach Car Configuration

Key Observations from the Fire Hazard Analysis

Fire hazard analysis can quantify the consequences of specific, interior fire scenarios on the safety of passengers and crew in typical intercity coach, sleeper, and dining cars. Such an analysis can provide information on:

- The largest fire that still provides sufficient time to

insure that passengers and crew are safe from unreasonable risk of death or injury from interior fires. For example, materials or products exhibiting fire growth rates at or below a medium t-squared level would provide sufficient time for egress for the design fires considered in figure 1.

- By comparing the largest design fire to specific fire scenarios involving materials used in the construction of passenger trains, the acceptability of the materials can be judged. For example, materials and products that comply with the current FRA requirements for fire performance exhibit fire growth rates below the medium t-squared level, and thus would be acceptable under the design criteria presented in figure 1.

There are significant uncertainties worthy of note. These are the quantity, arrangement, and fire performance characteristics (ignitability and fire growth characteristics) of items brought aboard by passengers as baggage and materials brought aboard as supplies such as packaging materials associated with food or cleaning supplies. Cone Calorimeter tests and assembly tests show that there are train car materials that can represent significant sources of heat as secondary fuels. The wall carpet and its adhesive, for example, resist ignition, but can produce a high HRR when exposed to a large fire insult. Still, for all but the most severe ignition sources, conditions in all three designs studied remain tenable sufficiently long to allow safe passenger egress.

The effects of severe fire scenarios may be potentially mitigated by precluding any fire having a fire growth rate of faster than medium t-squared, or modifying the egress system. For example, the severe scenario where all components are ignited by a large trash bag has been addressed by Amtrak through a redesign of trash containers and modification of operational procedures to ensure large accumulations of trash are not present in the cars.

EVALUATION OF MODEL PREDICTIONS WITH FULL-SCALE TESTS

From the hazard analysis, the obvious question that arises is how good are the model predictions. The only widely-accepted method of verifying the model predictions is to test them against actual controlled experiments. Full-scale experiments were conducted to examine the model predictions.

Two different types of tests were conducted to evaluate the accuracy of the results of fire hazard analyses conducted: 1) a series of gas burner tests to evaluate the accuracy of the fire performance curves for an actual train car geometry and 2) a smaller series of tests to evaluate fire spread and growth for actual train car furnishings exposed to a range of initial fire sources. In a fire hazard analysis, the fire performance curves show the predicted response of the chosen car geometry to a range of typical fire growth rates and determine the available safe egress time from a car exposed to an arbitrary fire. These calculations are then compared to the time necessary to evacuate passengers from the car to determine the largest fire growth rate and size that is allowable for a chosen car geometry. To evaluate the accuracy of the model calculations of the fire performance curves, a series of gas burner fires covering a range of fire size and growth rate were used to experimentally determine a fire performance curve for an actual train car. The experimental fire performance curve determined from temperature and gas concentration measurements made during

the tests can then be compared against the predicted fire performance curve to determine any differences and their significance.

Figure 2 includes a fire performance graphs determined from experimental measurements in the gas burner tests along with fire model predicted curves calculated for the test vehicle. For a medium growth rate t-squared fire, the time to incapacitation determined from the replicate gas burner tests was (126 ± 7) s. For other growth rate fires, the time to incapacitation ranged from (40 ± 4) s for the ultra-fast growth rate fire to (230 ± 12) s for the slow growth rate fire. On average, the uncertainty of the experimentally determined times to these untenable conditions was less than 7 % (based on one standard deviation).

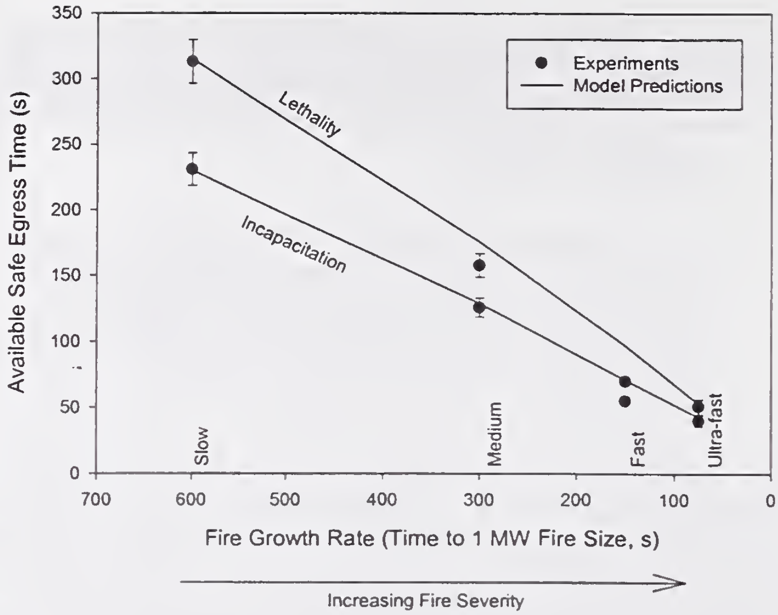

Figure 2. Comparison of Experimental and Predicted Fire Performance Curves for Incapacitation and Lethality in a Coach Car.

Key Observations from Full-Scale Tests

Visually, the comparison between the experimentally determined fire performance curves and the curves calculated with the CFAST fire model is quite good. The relative difference between experimental and calculated times averages 13 % for all fire growth rates and both tenability criteria. Comparisons of model predictions with experimental measurements more typically show agreement within 20 % to 25 % percent. Thus, the average agreement of 13 percent for these calculations should be considered excellent.

SUMMARY

This paper has presented an overview of an ongoing research project intended to demonstrate the use of heat release rate measurements and hazard analysis techniques when applied to passenger train fire safety. The results of this project are intended to: (1) provide additional information useful in refining existing fire safety provisions, and (2) allow car builders and passenger train system operators design flexibility to employ a broader array of materials and designs in future passenger rail cars. The successful application of this approach to complement material screening tests could provide a more cost-effective way to evaluate the real-world fire performance of passenger train materials.

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APPROACH TO EFFICIENT SYSTEM OF BUILDING CONTROL

Naohiro Takeichi
Associated researcher, Building Research Institute,
Tsukuba, Japan

ABSTRACT

In the industrialized countries, the authorities have been preparing revisions of building control systems including performance-based code for the global market, encouragement of technical innovation, etc. The purpose of this paper is to apply the economic theory, including market failure and government failure, to the construction market to discuss more efficient approaches to secure the performance of buildings and their components.

INTRODUCTION

There are many kinds of regulations to keep public safe and healthy. Regulations have been established when some serious accidents occurred, or when some individuals or organizations alerted the hazards to become serious social problems. The public sectors of national and local government and parliament have established and reinforced the regulations each time when serious damages have made to the society. But the some economist and industries criticize that overdoing to regulate makes economic stagnation.

Primitively the Japanese constitution guarantees the maximum freedom of individual activities, but it also permits governments or other public authorities to have some regulations from the public welfare stand point. So buildings and dwelling houses have to be regulated to protect public health and safety although individual activities are limited. However there are some issues to be discussed whether the regulations applied reasonably. Also, the balance between public welfare and individual rights must be discussed.

In recent Japan, the economic depression still suffers the market. Government gets a power to refine and deregulate the overdoing regulations to revitalize industrial and individual activities. In the construction industry, the Building Standard Law is going to amend to introduce performance based code and inspections by private company. And also they instituted a dwelling performance indication system requiring builders and contractors 10-year guarantee on weather tightness and structure.

This paper will discuss several social systems based on recent market approaches as describes in previous paragraphs. The construction market, negative effects and their reasons will be discussed from the points of imperfect information and the externalities.

NEGATIVE EFFECTS PRODUCED BY IMPERFECT MARKET

In many countries, including United States and Japan, most buildings and houses are built and dealt through the market. In economics, if the market condition functions properly, money, time, natural resources and other resources will efficiently used to satisfy the consumers' convenience. This means, consumers can satisfy their demand in low price, and suppliers will be able to earn maximum amount of money through the market with most efficient consumption of resources. In other words, efficient market means anyone cannot be made better off without making someone else worse off the allocation of resources. (No one cannot satisfy their demands without forcing others to sacrifice.) But unfortunately in the case of construction market, if there is no regulations or alternative actions, market cannot be efficient. And the case will be called "market failure".

As a client would like to satisfy his demands to build a building, the supplier doesn't positively meet client's claims except the part that the client can see and confirm. The other part, ones that the client cannot confirm in the real building or any plans at the contract, or ones that are required by the people, who are affected by the construction except the owner, are left unfinished. If their demands will not satisfied, there are sometimes negative effects to the final outcome. In the worst case, they must become social problems.

IMPERFECT INFORMATION

Generally it is known, that suppliers have much information about its products than consumers. This can also be applied to buildings. About a trade of a building or a house, a consumer cannot find out the performance differences of each component easily. For example, a consumer can not confirm its weather tightness, or earthquake resistant of the building that they would like to purchase.

And even for a small dwelling house is much expensive, consumers have few opportunities to buy them. Because of the consumers' little experience to purchase houses, it is difficult to make out good/bad about produts, dealers, and builders.

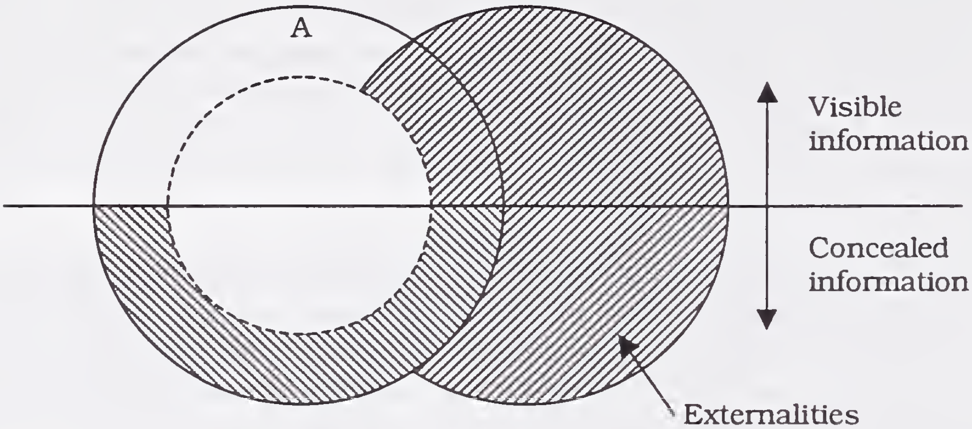
On the other hand, main aim of suppliers is pursuit of profits. To increase profits, they sell buildings in higher prices and larger quantities with additional value, if they cannot, then they cut down the price. In the case suppliers would cut down the price, they lower the performance of some components that the client doesn't require or can't confirm.

If suppliers want to gain profit in short range of time, they may downgrade the performance, which is not disclosed by the purchaser at the time of the contract. However these efforts of the suppliers will be found in several years after the purchase of the product, or when an occasional disaster strikes. If the downgraded building performance include indispensable functions such as stability of foundation, fire resistance etc., safety and health of the human living inside will be put in to serious danger.

NEGATIVE EXTERNALITY

There are variety of types and scales of buildings, including a house used by only a family or

Figure 1. Structure of the demands about he building performance



A. Demands that the client want
B. Demands that the neighborhood want
C. Achieved performances

The hatched: Demands that may affect badly though suppliers are passive to satisfy

huge complex used by thousands of people. Except for the building that stands alone and far from central city, building accommodates some influences not only to their owners and users but also to their neighborhoods. In economic the case is called a market failure with externalities. The externality is what a building has affected to the people, who is not related to contracts of the building, or products or service that are produce in the building, and who gets nothing against its effects.

The externalities include negative effects and positive ones. Examples of negative externalities are, injured of pedestrian caused by a collapsing of wall, and death of audience or injuries caused by fire in a theater.

Thoughts to reduce negative externalities are necessary, however it requires costs. The costs will be added to the sales prices of the goods finally, but both consumers and suppliers usually don't except additional price increase. The reductions of externalities are passive on the economic activities in the market. But if negative effects by externalities are not corrected, they often cause social problems.

REGULATION BY GOVERNMENT

On each contract in the market, suppliers act very positively to satisfy only the clear part of clients' demands, but they tend to be negative to the ones that cannot be confirmed easily, and ones by neighborhoods. But in the case that the demands are essential for public and owners, such as ones related their health and safety, some response for the market failure must need.

On the real society, there are already many responses for the market failure. And the public sector including government has a big role. National and local governments provide legal framework that describes essentials for buildings, they collect information by checking plans and inspections, and directly execute amendment or demolition of illegal buildings.

In the inspections, against the component of a building that cannot be decreased during the entire life cycle of the building, inspections have to be done before it is covered in a wall or under a floor. On the other hand, inspections against the equipment, which has to be maintained regularly, such as fire detector or sprinkler, inspections should be done every time when the equipment's reliability is no longer functional.

GOVERNMENT FAILURE

Government often intervenes against the market failure. However even government cannot avoid failures in many cases that cannot get good results people want.
One reason of government failure, which is "the imperfect information" also, makes a problem for public sector as well as private sector. Even government cannot get information of building performance perfectly. Many indispensable performances of building parts like structures including basement, columns, beams and their joints are concealed. And those are too many members to inspect economically. And there is another point in the real society. Not so few men are willing to cheat inspectors and making negative impacts for consumers and citizens. In Japan, because of negligence of builders the defective components of dwelling houses have become a major problem among society.

Also in recent Japan, there is a criticism of the efficiency of government and less flexible application of regulation on the points of demands and procedures. On legal framework, citizens who have suffrages should control government, but it is difficult to assess the efficiency and achievement of goals of the policy.

And in the real construction industry, it is important that a *building and their components satisfy regulations.* So many suppliers have no incentives to provide better (or bad) performance products than required on regulations. This means that in the market there are same products in same levels that are not related to consumers' interests. This quality level won't change even if public needs are changed, unless the regulations are amended. However, revisions of regulations or to replace them with new regulations require long terms and huge efforts. Therefore regulations tend to be stable.

ALTERNATIVE APPROACHES

Some alternative approaches to government failures are devised. Performance based code

system and inspections by private sectors, are expected to add flexibility to the procedures to regulate. These new system will be introduced into the new revision of the Building Standard Law.

Performance based code system is expected to encourage material makers in development of new materials, and designers in new structures or dramatic interiors that cannot be built or forced extra efforts to fit to the current conservative prescriptive regulations. Also the inspection by private sectors will introduce competitive theory to the conventional inspection procedures, and it is expected to improve total inspection procedure, including the reduction of the inspection term.

Alternative approaches instead of government intervention have been also discussed. Performance indication system will start soon in Japan. In this system, suppliers show the various performances of buildings which has been concealed from the consumers, and consumers are able to judge which performance are adequate or not from the disclosure sheets. Therefore, consumers are able to make a best choice which fits their needs. As consumers can judge the performances of the buildings, which were not visible before, it is an incentive for competitors to archive better performance. It is an attempt to improve the imperfect information that used to cause the market failure.

To handle this system properly, the judgement of the performances of constructions and parts sometimes requires specific knowledge. On the consumers' side, they should have the knowledge or deputize specialists, to do lead their way to good results. On the public side, it is necessary to provide the regulations with clear and easy expressions to make easily understandable for public.

And others - insurance, obligations of performance guarantee in terms and categories are worthy to consider.

SOLUTIONS

Historically, to maintain public health and safety, government has made regulations. But economists and industries have criticized their efficiency, and they have required deregulation or removals of the overdoing regulations. However we have to carefully consider the case that there are externalities that can't be corrected due to little incentives to participants in the market, and also the case that it is difficult to break up the imperfect information. If problems of private incentives and imperfect information cannot be solved, construction market will not revitalized even though the government deregulates the regulations.

In the construction society, the discussion regarding worth, efficiency, and methods of regulations just start. However such as EU, the construction market is rapidly unified to a global market. Designers, constructors, materials, construction methods etc can easily jump the border. To secure the public health, and to archive efficient systems, it is necessary to study and discuss more widely and deeply.

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FIRE SUPPRESSION

FIRE SUPPRESSION RESEARCH IN THE UNITED STATES: AN OVERVIEW

Richard G. Gann
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8650

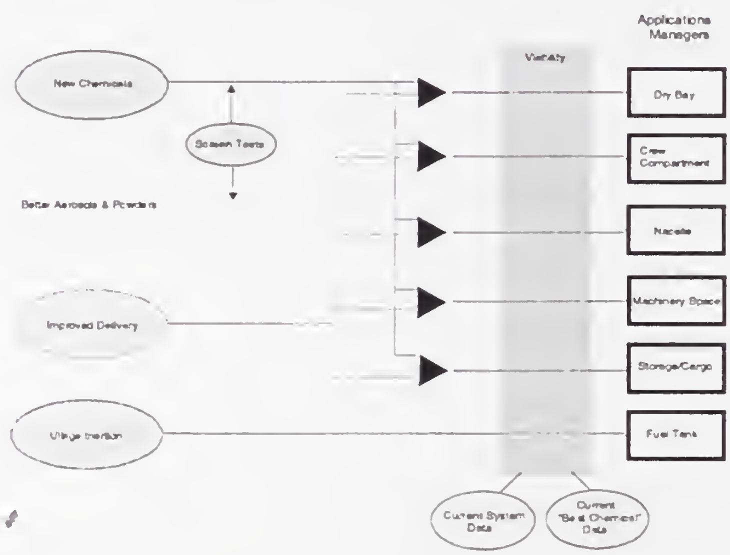
ABSTRACT

Since the 14th UJNR meeting, significant progress has been made in understanding fire suppression. Most of this has been derived for halon-like applications, with some efforts on suppression by water and water-based solutions.

1. HALON ALTERNATIVES

Most U.S. research on halon alternatives is sponsored by the Department of Defense (DoD) Next Generation Fire Suppression Technology Program (NGP). This program has the goal of developing by 2005 halon 1301 replacement technologies for aircraft, ships, and land combat vehicles (Figure 1). Beginning in FY2000, the NGP will focus on fire suppression needs for aircraft dry bays and engine nacelles: new chemicals, verified precepts for improved suppressant delivery, and validated modeling to guide the selection of optimal dispensing conditions, nozzle locations, etc. Additional information on the NGP can be found at www.dtic.mil/ngp/ and in the endnotes in [1,2]. Much of the overall U.S. research progress has been reported in the Proceedings of the annual Halon Options Technical Working Conference [3,4].

Figure 1. NGP Research on Retrofitable Fire Suppression Technologies



In searching for new chemicals that perform as well as CF_3Br but without the environmental limitation, a comprehensive view of fire suppression has emerged. Catalytic agents, such as CF_3Br and metal compounds, reduce the superequilibrium levels of flame radicals toward equilibrium levels. Adding heat capacity reduces the flame temperature and thus the flame reaction rates below the level needed to sustain combustion. Thus there is a non-linear relationship between the chemical (catalytic) and thermal contributions of a suppressant.

There are new findings on several promising suppressant chemicals:

$H_3COC_4F_9$ (HFE-7100) was shown to be an efficient non-chemically-active suppressant [5]. About twice the mole percent of the gas as halon 1301 vapor is needed to suppress a flame. As an aerosol, only half the halon 1301 vapor level is needed.

Small mole fractions (*ca.* 10^{-4}) of $Fe(CO)_5$ are near the ideal limit at reducing premixed flame velocities [6,7]. At higher concentrations the agent becomes less efficient, as the active iron species condense to form relatively inactive particles. Ferrocene is nearly identical, indicating no dependence on the binding of the iron. Manganese-containing compounds behave similarly, but are 5-7 times less efficient at reducing burning velocity.

Also of interest are tropodegradable bromocarbons [8]. Bromoalkenes will have atmospheric lifetimes of a few days. A series of bromofluoroalkenes and bromofluoroamines generally had cup burner extinguishment values below about 0.04 mole fraction in air. Rats exposed for 30 min to 0.05 mole fraction (in air) of four of the compounds (1-bromo-3,3,3-trifluoropropene, 2-bromo-3,3,3-trifluoropropene, 4-bromo-3,3,4,4-tetrafluorobutene, and 2-bromo-3,3,4,4,4-pentafluorobutene) showed no ill effects. The Ames tests were also negative.

A set of efficient, accurate screening tests for new suppressant chemicals is near completion:

The Dispersed Liquid Agent Screen (DLAS), based on the Tsuji diffusion burner, is now in use both to obtain suppression efficiency data and as a research tool. [9]. The Transient Application, Recirculating Pool Fire (TARPF), a screening tool for the effectiveness of suppressants that are impulsively discharged [10], is nearly complete. An injection system for the effluent from solid propellant gas generators has been tested.

A tiered screening system for environmental impact, toxicity, and materials compatibility has been developed [12]. A physiologically based pharmacokinetic (PBPK) model of a human system to describe the short-term inhalation of volatile halogenated hydrocarbons and their transport to the bloodstream is nearing completion. Development of a computational screen for a suppressant's atmospheric lifetime and infrared absorption is continuing. Calculations for the reactions of OH with several fluoroethanes and the ethers derived from them have reproduced the experimental trend [13].

The suppression of ignition in electrically energized equipment is a problem of high impact. The temperature of a metal surface needed for ignition of ethylene/air mixtures rose in the presence

of a number of thermally active suppressants (N_2, IG-541, HFC-23, HFC-227ea, FC-218, and FC-3-3-10). Near 1000 °C surface temperature, the ignition prevention levels of all these agents exceeded current design concentrations [14].

Nearly all current suppressants of interest emerge from pressurized storage containers as liquids or powders, along with a gaseous component. The properties of the aerosol determine efficiency of transport effectiveness to the fire, of suppression of gaseous and condensed-phase fuels, and of ignition prevention.

> Studies of water droplets injected into non-premixed flames have identified the optimal droplet diameter ranges for suppression. Droplets with diameters ≤ 18 μm evaporated, a desirable behavior; many with diameters ≥ 30 μm survived and were much less efficient at suppression. Droplet diameter variation was found to have a minimal impact on flame spread rate across a PMMA surface. However, buoyancy has a significant impact on the droplet velocities and diameters [15].
>
> It is possible to adsorb a suppressant onto an inert host for transport to the fire: a mass fraction of 33 % of $Fe(CO)_5$ onto zeolites and up to 200 % aerogels. At 250 °C a large fraction of the $Fe(CO)_5$ is desorbed. Flame tests will determine whether the desorption is fast enough.

The complement to identifying new agents is improving their transport to the fire site.

> Replacement fluids must function within the existing distribution plumbing for cost reasons. A new computer code for prediction of two-phase fire suppressant flows plus pressurizing gas in distribution piping is now nominally complete, and a test facility has been constructed to verify the results. Measurement capabilities include instantaneous mass flow of fluid during transient discharge from the source vessel, fluid temperatures along the discharge pipe, and void fraction. Numerous data have been collected using HFC-227ea.
>
> Halon 1301 systems are overdesigned to effect good agent distribution in cluttered spaces. For new agents, these penalties need to be quantified for different fuels and obstruction shapes. A model based on a well-stirred reactor accurately captures the experimental time for agent entrainment into the recirculation zone. A suppression system should provide a critical agent concentration for at least 3-4 times this mixing time [16].
>
> NGP research is developing new types of solid propellant gas generators (SPGGs) that have high flame suppression efficiency, yet little negative impact on the environment or the weapons system. The first of these formulations are aimed at both reducing SPGG combustion temperatures and increasing flame suppression efficiency.

The success of new technologies requires instrumentation to identify their effectiveness.

> NGP researchers have developed a time-resolved (10 ms), multi-point, fieldable, fiber-coupled, near-infrared tunable diode laser-based sensor for measurement of combustible

mixtures of oxygen and hydrocarbon fuels (heptane and JP-8) before, during and after the fire suppression event of 250 ms duration.

Research is also continuing on developing instrumentation for measuring agent concentration with a 10 ms time response, fast enough for quantification of the transient agent concentration during the suppression of the fastest fires involving military systems [17].

A decision to retrofit a fire suppression system (or not) must address a number of objective cost factors and subjective value factors. Accordingly, the NGP is developing a methodology to quantify a fire suppression technology by its total life cycle cost and to enable superimposing on this a subjective value system [18].

Research on fuel tank inerting has been limited. The Air Force is considering the use of CF_3I.

II. WATER AND WATER-BASED SUPPRESSANTS

There has also been research progress in learning how aqueous suppressants are effective and applying the new knowledge to their selection and use.

Computational modeling of sprays of sprinkler droplets has been used to learn about their penetration of fire plumes. Increasing droplet size is more effective than increasing spray momentum [19]. New work [20], reported in this proceedings, is underway to model and predict the water density resulting from a discharged sprinkler.

Prompted by observations that residential sprinkler delivery rates have dropped below the norm, additional research and testing has been performed [21]. Modifications to the delivery criteria and test procedures are pending at UL and NFPA.

The first validated prediction tool for multiple sprinkler activation was produced [22]. The study included the interactions with vents and draft curtains.

Other sprinkler-related research issues under consideration include: measurement of the corrosion of sprinkler piping systems, understanding the effect of ceiling height on sprinkler performance, and evaluating the available tools and technology for designing performance based sprinkler systems.

Aqueous solutions of protein-based foams and gels are sprayed onto surfaces (such as exterior walls of houses) as a temporary measure to prevent ignition from exterior fires. Testing methodologies for these solutions have also been evaluated for their ability to differentiate their effectiveness on Class B and Class D fires relative to water [23,24]. Laboratory experiments have provided guidance for capitalizing on their thermal and ablative properties [25].

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OVERVIEW ON PROGRESS OF FIRE EXTINGUISHING RESEARCH AND TECHNOLOGY IN JAPAN

Naoshi Saito

National Research Institute of Fire and Disaster
3-14-1, Nakahara, Mitaka, Tokyo 118-8633, Japan

Introduction

In 2000, Japanese fire extinguishing science and technology face the following issues:

(1) Protection of the global environment,

(2) Decreasing water damage in fire fighting of residence fires,

(3) Promotion of the fire safety for old people in the aged society,

(4) Reduction of victims by urban fire after a large earthquake, and

(5) Fire protection in high technology industries by developing new method.

Here, the recent researches and development on the fire extinguishing in Japan are introduced according to these subjects.

1. Global environment and fire extinguishing

One of the most important subjects in the fire extinguishing science and technology is the prevention of the stratospheric ozone layer. Japan employs the two halon phase-out policies as follows:

1.1 Halon recycling

In Japan, there are about 55,000 halon fire extinguishing systems, and about 17,000 tons of halons are stored in the systems. "Halon Recycling and Banking Support Committee, Japan" is responsible for the recycling, banking, and preventing illegal discharge of the halons. The recycling halons are used mainly new fire extinguishing systems for very important facilities, like a telecommunication facility, a museum, etc., and to replenish the exiting halon extinguishing systems. Large tanks with floating roof in refineries and stockpiling bases of oil are equipped with the halon 2402 system for protecting against a weather seal fire of the floating roof. There has not yet been an appropriate replacement for the fire extinguishing system. For the recycling of Halon 2402, Nakada et al. [1] researched the quality and fire extinguishing capability of Halon 2402 stored for form 16 years to 27 years in the systems. They did not find any problems to use the Halon 2402 without further purification.

1.2 Employment of halon replacements

(a) Gaseous fire suppressants

Since 1995, about 600 fire extinguishing systems of halon replacements have been employed in Japan. Inert gas agents of IG541, IG100, and IG55 were employed by 75 % of the systems, and the rest 25 % used HFC suppressants. NRIFD researches the fire extinguishing capability of the agents under the various application conditions. Saito et al. [2] studied the effect of combustible vapors mixed in air on flame extinguishing concentrations to install the equipment in the facilities where hazardous materials are handled. Sakurai et al. [3, 4] studied flame extinguishing concentration of inert gas agents for methane and propane flames, and discussed the meaning of such data for the gaseous combustibles.

There are basic researches to prepare the development of high performance agents. Saso et al. [5, 6] reported the simulation results of burning velocity of trifluoromethane-methane mixtures, and tried to explain the difference of temperature effect between CF_3Br and CHF_3 agents.

Since the efficiency of almost all halon replacements are not better than halon 1301, the safety factor of design concentrations has to be smaller than that of halon 1301. This fact requires the more spatial uniformity of the agent concentration in the compartment. For verifying the system design, there is a joint research between NRIFD and University of Tokyo to develop a computer cord for simulating the flow and mixing process of discharged fire suppressant [7-9]. On this subject, Makarov et al. [10] simulated the mixing process of discharged IG541 in a full-scale model of a mechanical car parking system. Tsuruda et al. [11] report the above simulation results in this meeting.

Japanese users are very interested in the information of a toxic hazard of the products generated in fire extinguishing form the gaseous fire extinguishing agents. Saso et al. [12] studied CO formation in the flames inhibited by halon replacements. Recently, FDMA (Fire and Disaster Management Agency, Ministry of Home Affairs) also started a research project on the overall safety of fire extinguishing by the halon replacements under the direction of "Committee for Safety Assessment of Halon Replacements."

(b) Water mist

Water mist is expected as a total flooding agent of halon replacements, because water mist extinguishes the fire very effectively if it passes through a reaction zone in a flame and takes the heat away from the flame by the heat of evaporation. However, there are many difficulties to use the water mist as a total flooding agent.

There are a few researches on the basic fire extinguishing effect of water vapor since the last UJNR meeting. Ogawa [13] studied the effect of low concentration of water vapor on the

flammable limit of methane. Ogawa [14] also reported the suppression effect of higher concentration of water vapor in the meeting. Danbara et al. [15] studied the effect of water vapor on flame spread rate over the filter paper surface. They concluded that the extinguishing effect of low concentration water vapor is essentially thermal.

For the water mist, Morita [16] introduced "Extinguishing Compartment Fires by Water Mist" in this meeting. Yashima [17] studied the quenching effect of water spray on propagating flames in premixed gases. Asami [18] measured actually delivery density of water spray for propane diffusion flame.

The application research of a micro-fog system was conducted by Kikkawa et al. [19] for a full-scale dwelling house used in South Pole. Irie et al. [20] and Takemoto et al. [21] carried out compartment fire extinguishing tests by a pressurized water mist system. FDMA studies the fire extinguishing method by water mist systems to prepare a standard.

2. Decreasing water damage in fire fighting

According to Japanese Fire Service Law, the fire extinguishing by water is a basic concept of the fire fighting. Therefore, the systems of fire hydrant, "drencher", and sprinkler have to be intrinsically desirable for the fire protection. However, the water system is not liked residents because of the water damage. Many local fire departments try to decrease the amount of water to extinguish residential fires. Noguchi et al. [22] reported a development of a pneumatic atomizing gun for fire fighting by the joint research with Yokohama Fire Department. Shimoju [23] tried to develop a sprinkler system minimizing water damage using a shape-memory alloy. Tsuji [24] studied "efficient fire extinguish sprinkler method." Kashiki [25] proposed a new fire fighting method by solutions of special polymers which suddenly change to viscous gels at the higher temperature form 310 to 340 K.

3. Fire safety for old people in the aged society

There are no fire extinguishing approaches on the subject since the previous meeting.

4. Reduction of victims by urban fire after a large earthquake

The study of fire fighting by helicopters is continued in NRIFD in cooperation with the fire departments of local governments. There are several experimental reports on the effect of this fire fighting method by Yamashita et al. [26, 27] and Takemoto et al. [28]. Hiraga et al. [29] studied the impulsive force of falling water in the aerial fire fighting.

5. Fire protection in high technology industries

A study of sodium fire is an old subject of alkali metal fires. After the fire accident of the fast

breeder reactor "Monju," many experimental studies have been conducted on the combustion phenomena and extinguishing of sodium fire by Saito et al. [30, 31]. They found combustion between sodium and sodium combustion products on a pool fire, and they think that the extinguishing by the inert gases as argon and nitrogen may be impossible [32].

Another important alkali metal fire is a fire of lithium ion battery cell factory. The battery cells are widely used in recent electronic instruments. Tsuruda [33] began to study this battery fire to find useful fire fighting method.

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An Investigation of Extinguishment by Thermal Agents Using Detailed Chemical Kinetic Modeling of Opposed Jet Diffusion Flames

William M. Pitts and Linda G. Blevins
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

Abstract

Thermal fire-fighting agents are being investigated as potential replacements for halons which can no longer be manufactured due to their deleterious effects on stratospheric ozone. This work describes a detailed chemical kinetic modeling study of methane planar opposed jet laminar diffusion flames burning in air diluted with various thermal agents. Extinction conditions are characterized as a function of agent concentration. Comparison of the calculated results for burning in nitrogen-diluted air with literature values for the extinguishing concentration allows the corresponding maximum flame temperature at extinguishment to be estimated as 1550 K. By applying this criterion, extinguishing concentrations are calculated for argon, helium, carbon dioxide, and water vapor. Calculated values are shown to be in good agreement with measurements in cup burners using heptane fuel. Surrogate agents having non physical behaviors have been used to characterize particular aspects of flame extinguishment by thermal agents. It is shown that dilution effects result from passage of oxygen through the flame front and that these effects should be accounted for when estimating the amount of a particular thermal agent required to extinguish a flame. By the use of a surrogate agent which absorbs heat by unimolecular reaction, it is demonstrated that the physical location of the heat extraction relative to the flame front does not modify the effectiveness of a thermal agent as long as the agent is subsequently convected into the flame zone.

1. Introduction

The manufacture of halons which have been widely used in fire extinguishing systems was banned in 1994 due to their deleterious effect on stratospheric ozone. As part of a coordinated effort to identify suitable halon replacements, the National Institute of Standards and Technology is investigating whether highly effective thermal agents are feasible. Thermal agents are defined as those which obtain their effectiveness solely by heat extraction and dilution. A great deal is known about the effects of thermal agents on flames. The paper by Sheinson et al. provides a good introduction [1]. There are a number of endothermic physical processes which can extract heat from a gaseous flame zone, thus lowering the temperature and ultimately leading to flame extinguishment. These include simple heating (i.e., heat capacity) of an agent, phase changes such as vaporization of a liquid or sublimation of a solid, endothermic molecular decomposition, and simple dilution. The flame temperature is also expected to be a function of the thermal diffusivity of an agent.

This paper describes a detailed chemical-kinetic modeling investigation of methane planar opposed-jet laminar diffusion flames (POJLDFs) burning in air diluted with various thermal agents

which is designed to provide an improved understanding of the extinguishment of fires by thermal agents. An internal report is available which summarizes the kinetic modeling in more detail and also includes the results of an extensive data base search of potential thermal agents and modeling results for the effectiveness of thermal agents in cooling liquid surfaces [2].

2. Detailed Chemical Kinetic Modeling

A series of methane POJLDFs have been calculated as a function of the counterflowing fuel and oxidizer velocities at the burner exits (assumed to have equal magnitudes, hereafter referred to as the *exit velocity*) and the concentration of various thermal agents added to the air side. For each concentration of added agent, an extinction condition is identified corresponding to a given exit velocity. A focus of this work is the identification of the minimum concentration of an agent required to extinguish buoyancy-dominated fires. The *extinguishing concentration* is expected to correspond to a particular POJLDF extinction condition. It will be shown in this paper that the extinguishing concentration can be related to a particular maximum flame temperature, T_{max}, observed for the POJLDF at extinction.

The code Oppdif [3] developed by Sandia National Laboratories and now available commercially from Reaction Design* was used for the calculations. After reviewing the literature, the widely used methane/air mechanism developed with the support of the Gas Research Institute was chosen for the calculations. The version used was GRI-Mech 1.2 [4] which consists of 32 chemical species undergoing 177 reactions.

In order to determine the extinction behavior for a flame, a stable burning solution was first obtained using a relatively low exit velocity. The resulting solution was then used as input for a calculation with a higher exit velocity. This process was repeated until the flame went out or a solution was not obtained. By approaching the extinction exit velocity in small increments, it was possible to calculate the extinction point to within a step size of 0.01 cm/s.

3. Modeling Results

Figure 1 includes a plot of T_{max} versus exit velocity calculated for a methane/air (0% added nitrogen) POJLDF. Air is assumed to be composed of 78.1% N_2, 21.0% O_2, and 0.9% Ar by volume. As expected, T_{max} decreases with increasing exit velocity. Extinction is calculated to occur at 320.12 cm/s with T_{max} = 1785 K. A number of parameters have been used in the literature to characterize the effects of varying exit velocities on POJLDFs. One of these is the maximum value of the velocity gradient element, a_o, observed on the oxidizer side outside of the boundary layer with a defined as

*Certain commercial equipment, instruments, or material are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

$$a = \frac{\partial u}{\partial z}, \qquad (1)$$

where z and u are the direction and velocity component normal to the flame sheet. The calculated value of $|a_o|$ for the methane flame at extinction is 509 s^{-1}, which is roughly 25% higher than measured experimentally [5,6,7]. Tanoff et al. have shown that calculated values of a_o are dependent on the detailed mechanism used [8]. In their work GRI-Mech also overpredicted a_o.

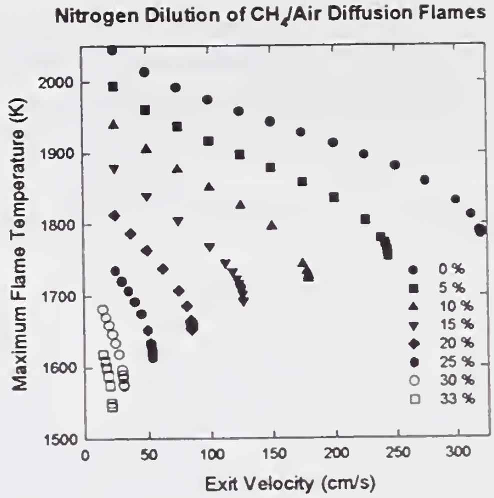

Figure 1. Maximum flame temperatures are plotted versus exit velocity for methane flames burning in air diluted by various percentages of added nitrogen.

We have identified only a limited number of experimental measurements of extinguishing concentrations for methane flames burning in air diluted with thermal agents. Most are for nitrogen. Simmons and Wolfhard [9], Ishizuka and Tsuji [10], and Puri and Shesadri [11] reported extinguishing mole fractions of 0.338, 0.319, and 0.286, respectively, for various types of opposed-flow flames. Ural has recently reported an extinguishing nitrogen mole fraction of 0.271 for a coflowing methane diffusion flame [12]. For the purposes of this work we have chosen to average the two higher experimental values to obtain a mole fraction of 0.33 added nitrogen as being representative of the extinguishing concentration.

A series of calculations was performed for methane POJLDFs reacting with air containing various percentages of added nitrogen. Figure 1 shows the results. As the percentage of added nitrogen increases, the exit velocities sufficient to induce flame extinction decrease. T_{max} at extinction also decreases with increasing nitrogen concentration. Plots of T_{max} versus exit velocity become steeper with increasing nitrogen concentration.

As stated earlier, the nominal experimental extinguishing mole fraction of nitrogen is 0.33. The calculated T_{max} at extinction for this condition is 1545 K. This is close to the experimental value of 1483 K reported by Ishizuka and Tsuji [10]. Both the calculated and experimental estimates for T_{max} at extinguishment are consistent with others in the literature [1,13].

For the extinguishing concentration of nitrogen, the extinction exit velocity is calculated to be 21.42 cm/s. The corresponding value of $|a_o|$ is 27.0 s^{-1}. An important question concerning the extinction of diffusion flames is: what strain rate is appropriate to use when determining an extinguishing concentration? The only literature discussions of this point identified were presented by Hamins et al. [14] and Saso et al. [15]. These authors compared extinguishing concentrations for a variety of agents determined with cup burners fueled with heptane [14,15] and ethanol [15] with corresponding results for counterflow flames. The counterflow measurements were made over a range of exit velocities characterized in terms of global strain rates, a_g. When the agent concentrations were comparable to those which induced extinguishment in the cup burner, a_g values reported by Hamins et al. were roughly 50 s^{-1}, while Saso et al. reported a_g values of $\approx$ 30 s^{-1}. Due to use of different boundary conditions and fuels

between the current investigation and those of Hamins et al. and Saso et al., as well as the use of different definitions for the characteristic strain rates, absolute quantitative comparisons are not appropriate. However, it is clear that the characteristic strain rates are of comparable magnitude. It is important to note that the characteristic strain rates appropriate for characterizing extinguishing conditions are much lower than typically used for experimental and modeling investigations of opposed-flow diffusion flames.

It is interesting to speculate why flames subject to Earth's gravity apparently cannot be sustained below a well defined characteristic strain rate. The most likely reason is that buoyancy effects place a limit on the lowest characteristic strain rates present in the flame. Buoyancy always accelerates hot combustion gases relative to the cold oxidizer, with the result that flame surfaces are subject to nonzero strain rates. The results of Hamins et al. [14] and Saso et al. [15] along with the current findings suggest this strain rate limit is on the order of a few tens of inverse seconds.

As already noted, no additional measurements of extinguishing concentrations for other thermal agents added to methane/air diffusion flames were identified. However, Ishizuka and Tsuji did make measurements for methane burning in an artificial "air" consisting of 21% oxygen and 79% argon [10]. This "air" was diluted with argon until extinguishment occurred. The extinguishing mole fraction for added argon was 0.543. T_{max} at extinguishment was 1443 K, or roughly 40 K less than for standard air diluted with nitrogen. A series of calculations for methane flames burning in argon "air" diluted with argon were carried out in the present work. A flame burning in argon "air" with 54% added argon is calculated to undergo extinction with T_{max} = 1473 K and an exit velocity of 15.9 cm/s. If one simply assumes that extinguishment occurs for the same T_{max}, i.e., 1550 K, as for the nitrogen-diluted air flame, an estimate for the required concentration of added argon of 52% is obtained. This is only 4% less than the experimental value. Thus, assuming that flame extinguishment occurs for the agent concentration necessary to reduce T_{max} at extinction to 1550 K should provide an excellent estimate for the mole fraction of an arbitrary thermal agent required to extinguish a fire. This approach was adopted for estimating extinguishing concentrations.

POJLDF calculations have been used to estimate the required extinguishing concentrations for methane burning in air diluted with Ar, He, CO_2, and H_2O. Water is assumed to be a gas even though at room temperature the required concentrations in air correspond to supersaturated conditions. Each of these gases is expected to act primarily as a thermal agent. The resulting plots (not shown) of T_{max} versus exit velocity exhibit trends similar to those for nitrogen shown in Figure 1. Estimates for extinguishing concentrations are tabulated in Table 1.

As already discussed, the only experimental values of extinguishing concentrations for thermal agents added to air we have identified for methane diffusion flames are for nitrogen. Cup burner determinations of extinguishing concentrations using heptane as fuel have been reported for some of these agents by Sheinson et al. [1], Babb et al. [13], Hamins et al. [16], Moore et al. [17], and Saito et al. [18]. These are summarized in Table 1. The maximum difference between values calculated for methane and the experimental values for heptane is 12%, with the vast majority being less than 10%. Overall, the cup burner measurements tend to be somewhat lower than for

Table 1. Extinguishing Concentrations (Mole Fraction) of Thermal Agents

Thermal Agent	Current Work	Cup Burner [1]	Cup Burner [13]	Cup Burner [16]	Cup Burner [17]	Cup Burner [18]
Nitrogen	0.33	0.30	0.33	0.32	0.30	0.34
Argon	0.43	0.41	-	0.41	0.38	0.43
Helium	0.34	0.32	-	0.31	-	-
Carbon Dioxide	0.22	0.21	0.20	0.23	0.20	0.22
Water	0.28	-		-	-	-

the counterflow flame. These differences could be due to the use of different fuels or to the effects of burner configuration. The close tracking of the calculated results and the experimental findings suggests that detailed chemical kinetic modeling can accurately predict the amount of a thermal agent required to extinguish POJLDFs and cup burner flames.

The differences in the extinguishing concentrations of helium and argon seen in Table 1 are interesting since both are monatomic gases and have identical molar heat capacities. The difference is clear in both calculated and experimental values. That helium is more efficient means that at least one other parameter, in addition to heat capacity, is important for determining extinguishing efficiency. A related observation was reported by Coward and Hartwell for the inerting of premixed flames which was attributed to the much higher thermal conductivity of helium which distributes the heat of combustion over a larger region of space and therefore weakens the flame [19]. The same explanation is likely valid for diffusion flames. Sheinson et al. reached the same conclusion [1].

An important advantage of modeling investigations is the ability to perform calculations for conditions which are not physically attainable in order to learn details concerning the role of various parameters. One question which has been the subject of speculation is the relative importance of heat extraction and dilution on the effectiveness of a thermal agent. To obtain insights into this behavior, an artificial agent was created by starting with argon and setting its heat capacity to zero. Direct comparison with the results for air diluted with argon allows the relative roles of heat extraction and dilution to be characterized. Sheinson et al. have discussed the effects of dilution on extinguishment [1]. They concluded that such effects are relatively small compared to direct heat removal due to heat capacity for the thermal agents CF_4 and SF_6.

Figure 2 is a plot of T_{max} versus exit velocity for the zero-heat-capacity argon added to air. This species decreases the strength of the flame as indicated by a reduction of T_{max} at extinction, but its effect is much smaller than for argon. The extinguishing concentration is estimated as 73%, or roughly 1.7 times the amount required for argon. This corresponds to an oxygen concentration of 5.7%. Assuming that the effects of heating an inert and dilution are additive and linear in concentration, the effectiveness of Ar as a thermal agent is estimated to be 59% due to dilution and 41% due to heat extraction. Comparison of the detailed flame structures for methane flames in air and in air diluted with zero-heat-capacity argon shows that the reason for the weakening of the flame burning in the diluted air is the passage of more oxygen through the flame to the fuel side. The unreacted oxygen which leaks through the flame front acts as a thermal agent.

One of the goals of this work was to test whether the effectiveness of a thermal agent depends on the location, relative to the high temperature flame zone, where heat extraction occurs. A surrogate thermal agent, X, was used for this purpose. The molecular weight, thermodynamic properties, and transport properties of X are identical to those of argon, but it can react unimolecularly in the presence of ambient gases to generate a new species, Y, i.e.,

$$\mathrm{X} + \mathrm{M} \rightarrow \mathrm{Y} + \mathrm{M} \quad . \tag{2}$$

Y is also very similar to argon, the only difference being that its heat of formation is assigned an arbitrary positive value instead of being zero. As a result, when Reaction (2) takes place it extracts heat and cools the local surroundings by an amount equal to the heat of reaction, $\Delta H_{X\text{-}Y}$. Since X and Y do not react with any other species, the reaction is simply a heat sink, and therefore meets the definition of a thermal agent.

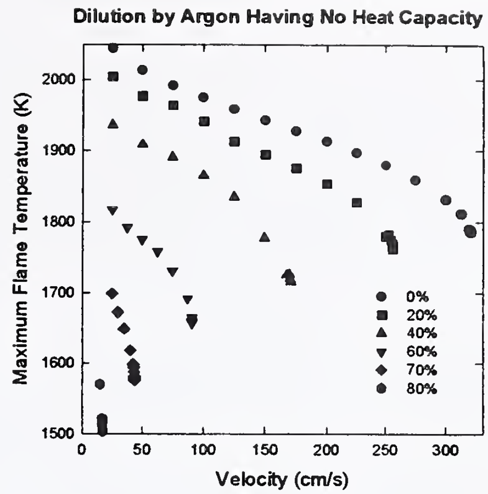

Figure 2. The maximum flame temperature is plotted versus exit velocity for a fictitious thermal agent identical to argon, except for its heat capacity which is set to be 0 J/mole-K.

The rate constant for Reaction (2) is expressed as

$$k_{\mathrm{X}\rightarrow\mathrm{Y}} = A\,T^{\beta}\,e^{-E_a/RT} \;, \tag{3}$$

where A is the pre-exponential factor, β is the temperature exponent, E_a is the energy of activation, R is the gas constant, and T is temperature. By varying the parameters A, β, and E_a it is possible to change the rate and temperature range over which the reaction occurs and hence the location relative to the flame zone for heat extraction. For the calculations which follow, initial values were maintained for A and β, and only the value of E_a was changed in order to vary $k_{\mathrm{X}\text{-}\mathrm{Y}}$.

Figure 3 compares calculated flame temperature versus distance from the fuel exit for two flames having exit velocities of 25 cm/s and with 5% X added to the air. For each $A = 1\times10^{10}$ cm^3/(mole-s), $\beta = 0$, and $\Delta H_{X\text{-}Y} = 96.1$ kJ/mole. The only difference between the two calculations is the value of E_a which equals 25.1 kJ/mole for one and 50.2 kJ/mole for the other. For the lower E_a, X begins to react immediately upon leaving the oxidizer exit which results in the temperature drop evident on the oxidizer side in Fig. 3 for positions well removed from the flame zone. When the E_a is increased to 50.2 kJ/mole the conversion of X to Y is very slow at room temperature, and there is no significant drop in temperature in the ambient region of the flow. However, as the temperature increases, X begins to convert to Y, and heat is absorbed in the higher temperature flame regions. Interestingly, T_{max} are identical within the minor variations observed in the calculations. Since flame extinguishment depends primarily on this parameter, it is concluded that the effectiveness of a thermal agent is independent of the spatial location where the heat extraction occurs as long as the gases are convected into the flame zone.

A complete set of calculations was carried out for X having $\Delta H_{X\to Y}$ = 96.1 kJ/mole and E_a = 41.8 kJ/mole. The extinguishing concentration for X is estimated to be 16%. The corresponding value for argon was 43%. Thus the heat extracted by the reaction of X to Y has reduced the amount of agent required by nearly 2/3. The effect of doubling the heat absorbed by X was considered by running a series of calculations for $\Delta H_{X\to Y}$ = 192.1 kJ/mole. From these results the extinguishment concentration for X with the higher heat absorption was estimated as 9.7%. This value is roughly 60% of that found with $\Delta H_{X\to Y}$ = 96.1 kJ/mole, or 20% higher than would be expected if flame extinguishment was dependent solely on the amount of heat extracted.

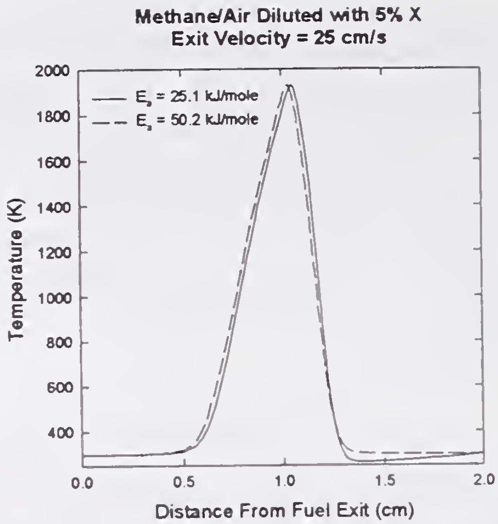

Figure 3. Calculated temperatures are plotted versus distance from the fuel exit for a methane flame burning in air diluted with 5% of a surrogate thermal agent X which can absorb heat by reacting to form Y. Results are shown for E_a = 25.1 kJ and 50.2 kJ.

The role of dilution has implications with regard to estimates of extinguishing efficiency for thermal agents which are often obtained by taking ratios of heat capacities for various gaseous agents. If the agents have a large heat capacity difference, and the percentages required for extinguishment therefore differ substantially, a simple linear dependence on heat capacity should not be observed. In fact, the agent having the largest heat capacity should be less effective than expected, as observed in the current calculations.

4. Summary

It has been shown that detailed chemical kinetic modeling can be used to make quantitative predictions of the amount of a thermal agent required to extinguish a fire. Comparison of the calculated and cited experimental results suggest that minimum characteristic strain rates in fires are on the order of a few tens of inverse seconds, corresponding to a POJLDF exit velocity of roughly 20 cm/s, and that T_{max} at extinction for the extinguishing condition is approximately 1550 K. The use of surrogate agents has revealed that dilution effects are due to an increase in the amount of O_2 bleeding through the flame front and that the role of dilution is relatively small as compared to heat absorption for all but monatomic species. The location of the heat absorption relative to the flame front does not affect the ability of a thermal agent to extinguish a flame as long as the agent is convected to the flame zone. While good qualitative estimates of flame extinguishing effectiveness can be obtained based solely on the ability of an agent to absorb heat, the estimates are not perfect due to dilution effects.

5. Acknowledgment

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Suppression of Low Strain Rate Flames by an Agent

Anthony Hamins, Matthew Bundy and Ishwar Puri*
BFRL, NIST, Gaithersburg, Maryland 20899-8640
*Dept. Mechanical Engineering, University of Illinois at Chicago, Chicago, Illinois 60607-7022

Abstract

The structure and suppression of low strain rate methane-air nonpremixed flames were investigated experimentally and computationally. Measurements of the critical suppression conditions were conducted using N_2, CO_2, and CF_3Br added to the fuel or oxidizer streams. Temperature measurements were made with small platinum thermocouples (0.025 mm wire diameter) that were coated with a fine layer (0.010 mm) of SiO_2 and corrected for radiative losses. Numerical simulations of the non-luminous diluted flames included radiative heat losses by participating gaseous species. A previously developed narrowband model of radiative transfer was incorporated into the one-dimensional flame simulation. For comparison, radiation was also modeled as an optically thin gray gas, represented by Plank mean absorption coefficients.

Introduction

The agent concentration required to achieve the suppression of low strain rate nonpremixed flames is an important consideration for fire protection in a microgravity environment such as a space platform. Currently, there is a lack of understanding of the structure and energetics associated with the suppression of low strain rate (<20 s^{-1}) nonpremixed flames, as well as the suppression effectiveness of agents in these flames [1]. The exception to this statement is the study by Maruta et al. [2], who reported measurements of low strain rate (a_g = 2 s^{-1} to 15 s^{-1}) suppression of methane-air diffusion flames with N_2 added to the fuel stream under microgravity conditions. They found that the nitrogen concentration required to achieve extinction increased as the strain rate decreased until a critical value (7 s^{-1}) was obtained. As the strain rate was further decreased, the required N_2 concentration decreased. This behavior was attributed to radiation-induced nonpremixed flame extinction. In terms of fire safety, the existence of a critical maximum value of agent concentration required for flame extinction represents a fundamental limit.

Agent suppression requirements of low strain rate counterflow flames are also important because they correspond to the agent suppression requirements in buoyancy dominated coflowing flames, such as cup burner flames. Counterflow flames are a convenient configuration for control of the flame strain rate. In high and moderately strained near-extinction nonpremixed flames, analysis of flame structure typically neglects radiant energy loss because the flames are nonluminous and the hot gas species are confined to a thin reaction zone where they are insufficient to cause significant radiative emission. For example, in counterflowing methane-air nonpremixed flames, radiative heat loss fractions with values ranging from 1 to 6 percent have been predicted and measured [3,4].

The objective of this investigation is to answer the following questions. (1) To what extent does radiation heat loss impact the extinction of a nonpremixed flame by an agent? (2) At

what strain rate does radiative loss become significant? Here, we report progress on answering these questions, as the competing processes of thermal radiation, flame stretch, and agent addition that lead to flame extinction are investigated. Measurements of flame structure and extinction were compared with simulations that included radiative heat transfer. In the experiments, a suppressant (N2, CO_2, or CF_3Br) was added to either the fuel stream or oxidizer stream of methane-air diffusion flames. These agents were considered because N_2 is an inert species that simplifies the interpretation of experimental results, CO_2 is a common fire suppressant, and CF_3Br represents a baseline for chemically acting agents.

Experimental Method

Experiments were conducted using a water-cooled counterflow burner with a diameter of 23.4 mm and a duct separation of 25 mm. Four 200 mesh stainless steel screens were secured at the opening of each duct to impose a top-hat velocity profile. The flow of dry air and methane (99.99% pure) were controlled using mass flow controllers that were calibrated using a dry cell primary flow meter with an uncertainty of better than 0.5%. The ratio of the velocity of the oxidizer stream to the velocity of the fuel stream was controlled (typically 3:1) to position the flame such that conductive heat transfer losses to the burner were eliminated, as verified by temperature measurements using thermocouples.

Extinction measurements were performed by incrementally increasing the agent flow, while maintaining a constant global strain rate, accomplished by simultaneously reducing the air or fuel flow. The global strain rate (a_g) was varied from approximately 8 s^{-1} to 45 s^{-1}, where for sake of comparison with Ref. [2], the global strain [5,6] is defined here as:

$$a_g = (-V_O/L)\cdot(1 + [V_F(\rho_F)^{1/2}/(-V_O(\rho_O)^{1/2})])$$

The parameters V and ρ denote the velocity and density of the reactant streams at the boundaries, L is the duct separation distance, and the subscripts O and F represent the oxidizer and fuel streams, respectively. Extinction measurements were repeated at least four times. The combined standard uncertainty (with a coverage factor of 2, i.e., k=2) in the agent extinction concentration based on repeat measurements and a propagation of error analysis was 1.3%.

In this study, flame unsteadiness was reduced by placing the burner in an enclosure ($0.5\times0.5\times0.6$ m^3), which isolated it from ambient flow disturbances and facilitated experimentation on flames with global strain rates (a_g) as low as 8 s^{-1}. The enclosure had a 10 cm exhaust port, with ventilation forced by a small pressure differential. For experiments involving CF_3Br, the enclosure was placed inside of a chemical hood.

Temperature measurements were conducted using 0.025 mm (0.001") diameter (Pt/Pt + 10%Rh) S-type thermocouples coated with a thin (0.01 mm) layer of silica. The thermocouple wires were oriented horizontally along an isotherm to minimize conductive losses. A small thermocouple was used to minimize the radiation correction to the temperature measurement and to minimize flame destabilization. This effect was quantified by measuring the N_2 concentration required to achieve extinction with the thermocouple at the position of peak temperature. The thermocouple presence cooled the flame 10 K and reduced the flame enthalpy by <0.5%. Radiation correction to the temperature measurements were made assuming a spherical bead shape using Ranz and Marshall's correlation for Nusselt number as described in Ref. [7], while the local Reynolds number was determined from the flame structure calculations. The emissivity

of the SiO_2 coating ($\varepsilon = 0.22 \pm 0.02$) was taken from Kaskan [8]. The radiation correction was 40 K at $T \approx 1600$ K, and was insensitive to the local velocity. The combined standard uncertainty ($k=2$) in the temperature measurement based on repeated measurements and a propagation of error analysis was 30 K, a value dominated by measurement variation.

Numerical Methodology

Numerical simulations of strained atmospheric methane-air flames were performed using a previously developed computer code [9] that employs detailed models of molecular transport and chemistry [10]. The use of counterflow codes to model inhibited nonpremixed flames is now routine, and the methodology is explained in detail elsewhere [3,11]. The agents considered in the simulations, N_2 and CO_2, are chemically inert, but the latter participates both as an emitter and an absorber in radiative transfer. The counterflow code does not include a buoyancy term in the momentum equation, so the simulations represent zero gravity conditions. A multi-dimensional code that accounts for buoyancy is being developed.

A term for the radiative heat loss rate per unit volume was added to the energy equation in the one-dimensional flame code [9]. Thermal radiation was modeled two ways. The temperature-dependent Planck mean absorption coefficients for participating gas species (CH_4, CO_2, H_2O, and CO) were obtained from Ref. [12]. A previously developed narrowband model for combustion-related radiation calculations was also implemented [13]. The mixture absorption coefficient for each isothermal layer (assumed semi-infinite) was calculated using the narrowband model, which uses a combination of tabulated data and theoretical approximations. The narrowband model calculates the radiative flux from a volume containing variable partial pressures of participating species (CH_4, CO_2, H_2O, and CO) [13]. The total directed radiated energy flux from the domain and its spectral distribution were calculated. The calculation implicitly assumes that radiative transfer occurs in the axial direction, which is consistent with the measurements of Lee et al. [3], who showed that the axial radiative flux is approximately six times greater than that emitted in the transverse direction. The value of the total flame heat release rate, Q, was quantified by summing the local heat release per unit volume (with contributions from each chemical reaction) and integrating this along the central axis of the domain. The radiative fraction is defined as: $\chi_R = Q_R/Q$.

Results and Discussion

Observations

Undiluted, low strain rate counterflow methane-air flames are luminous. As either CO_2 or N_2 was added to the oxidizer or fuel streams, flame luminosity decreased until, near extinction, the flames appeared to be completely nonluminous. (This was also observed for acetylene, a fuel that is extremely smoky under undiluted conditions.) The high inert content in the flames produces relatively cool temperatures, which precludes the formation of particulates that are otherwise present in the low strain flames. This observation motivated simplification of the radiation model for flames with CO_2 and N_2 added, permitting exclusion of radiative emission by particulate. This was not the case for CF_3Br, which when added to the methane-air flame, yielded a very luminous flame.

Suppressant added to the Fuel Stream

Figure 1 shows the measured N_2, CO_2, and CF_3Br concentrations in the oxidizer stream as a function of the global strain rate required for suppression. The most effective suppressant (on a volume basis) was CF_3Br, followed by CO_2 and then N_2. The critical suppressant concentration increased as the strain rate decreased, with the values leveling off near 15 s^{-1}, except for CF_3Br, which exhibited a turning point near 20 s^{-1}.

Figure 2 compares our measurements and calculations with the microgravity measurements of Maruta et al. and their numerical results, which were based on an optically thin gas assumption and an imposed duct separation distance of 8 cm. The experimental result from Refs. [6,14] are also shown, as are our simulations using both the narrowband and optically thin models corresponding to the conditions defined in Table 1 of Ref. 2. The three sets of calculations shown in Fig. 2 follow a gross trend similar to the measurements, but deviate from the measurements (and each other) at strain rates below 20 s^{-1}. The narrowband simulations predict that the fundamental limit occurs at a N_2 mole fraction, $[N_2]$, of 0.89 ($a_g = 2.3\ s^{-1}$), which is lower than the prediction based on the optically thin assumption, $[N_2] = 0.88$. This is expected, since the optically thin model does not consider reabsorption, and thus over-predicts radiative loss. The inclusion of reabsorption increases flame stability, similar to premixed flames [15]. At higher strains, radiation effects are less prominent and differences between the radiation models are less significant. The microgravity experiments from Ref. [2] were replicated in normal gravity, until the flames became unsteady for $a_g < 13 s^{-1}$, precluding confirmation of the turning point behavior for N_2 (see Fig. 2).

Suppressant added to the Oxidizer Stream

Figure 3 shows the measured concentrations of N_2, CO_2, and CF_3Br as a function of the global strain rate for agent added to the oxidizer stream. Consistent with Fig. 1, the most effective suppressant was CF_3Br, followed by CO_2 and then N_2. Flames with N_2 and CF_3Br addition showed turning point behavior at 20 s^{-1} and 15 s^{-1}, respectively. This was somewhat lower than observed when CF_3Br was added to the fuel stream (see Fig. 1), which may be due to differences in radiative emission, indicated by higher luminosity in the flames with fuel side CF_3Br addition.

The strain rate has a strong influence on flame stability. Figure 4 shows the calculated and measured concentration of CO_2 in the oxidizer stream required to extinguish the methane/air flames as a function of the global strain rate (a_g). The calculated and measured concentrations of CO_2 are in agreement, increasing as a_g decreases. At small strain rates, radiative heat losses are relatively more significant and consequently the amount of CO_2 required for suppression is lower than for the nonradiating flame case. Also shown in Fig. 4 are the calculated and measured maximum temperatures in the flames. The measured maximum flame temperatures decrease with decreasing strain rate, in agreement with the calculated trends. The flames also become spatially broader as the strain decreases. Differences in the absolute value between measurements and calculations are within 40 K, attributed to experimental uncertainty.

At a specified value of a_g, the calculated near-suppression maximum flame temperatures are nearly identical for all three radiation models. This suggests that regardless of the enthalpy loss mechanism, whether by thermal radiation or a combination of sensible heat extraction and

CO_2 dilution, the flames extinguish at nearly the same maximum temperature. This is in accord with the theory of flame extinction that holds that extinguishment occurs when heat losses are greater than heat production, independent of the mechanism.

At moderate strain rates (~50 s^{-1}), there is a negligible difference in the [CO_2] required for extinguishment using the three radiation treatments (Planck mean/optically thin, the narrowband model, and assuming adiabatic conditions, effectively ignoring radiative loss). At lower strain rates, however, as the relative importance of the radiation losses becomes significant, the agent required to extinguish a radiating flame is significantly lower that needed to extinguish a non-radiating flame. Because the narrowband model accounts for reabsorption of thermal radiation, there are lower enthalpy losses than the optically thin model and consequently the flames are more robust and require higher agent concentrations for extinguishment. Calculations yield $\chi_R = 0.010, 0.015, 0.028, 0.075$ for strain rates of 52 s^{-1}, 34 s^{-1}, 17 s^{-1}, and 5.7 s^{-1}, respectively. Even at very low strain rates, radiative loss accounts for only a small fraction of the flame heat loss, consistent with the results for N_2 addition flames [2].

Summary and Conclusions

The structure and suppression of methane-air diffusion flames was investigated through experiments and simulations. The competing processes of thermal radiation, flame stretch, and agent addition were characterized.

- The range of global strain rates investigated in normal gravity can be extended by isolating the burner in order to reduce disturbances by ambient currents, and by varying the velocity ratio of fuel and oxidizer to minimize conductive losses to the burner. Turning point behavior, where the agent concentration obtains a limiting value insuring suppression under all conditions, was observed in normal gravity diffusion flames.
- Diluted, low strain rate hydrocarbon-air flames are nonluminous near-suppression, which simplifies the treatment of radiation heat transfer in the calculation of flame structure. Flames with CF_3Br are luminous and particulate contributions to radiative emission should be considered.
- Flame structure calculations show that as the strain rate decreases, the flames broaden. Flame stability, as exemplified by agent concentration requirements for suppression, increases as the strain rate decreases, yet the peak flame temperature is found to decrease, both computationally and experimentally.
- Although the agent suppression requirements varied, the calculated peak flame temperature at suppression was the same when the radiation was treated as either optically thin, narrowband, or adiabatic, indicating that the flame temperature is independent of the heat loss mechanism.
- When radiative losses become significant, both the optically thin and narrowband models indicate that a limiting agent concentration (or turning point) occurs, whereas the non-radiating flame does not. Without a competing loss mechanism, the non-radiating flame continues to become more stable as its structure becomes broader. When radiative losses

become important, however, both convection and conduction losses compete with radiative losses, and flame stability no longer monotonically increases with decreasing strain rate.

Acknowledgements

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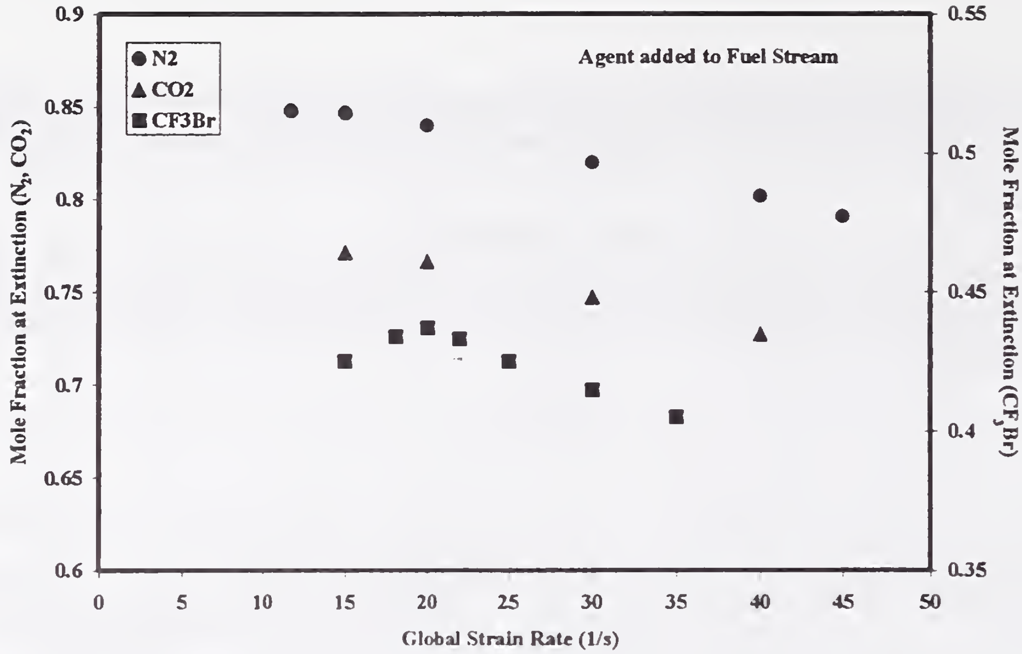

Figure 1. Measurement of the critical mole fraction of N_2, CO_2, and CF_3Br in the fuel stream of methane-air diffusion flames.

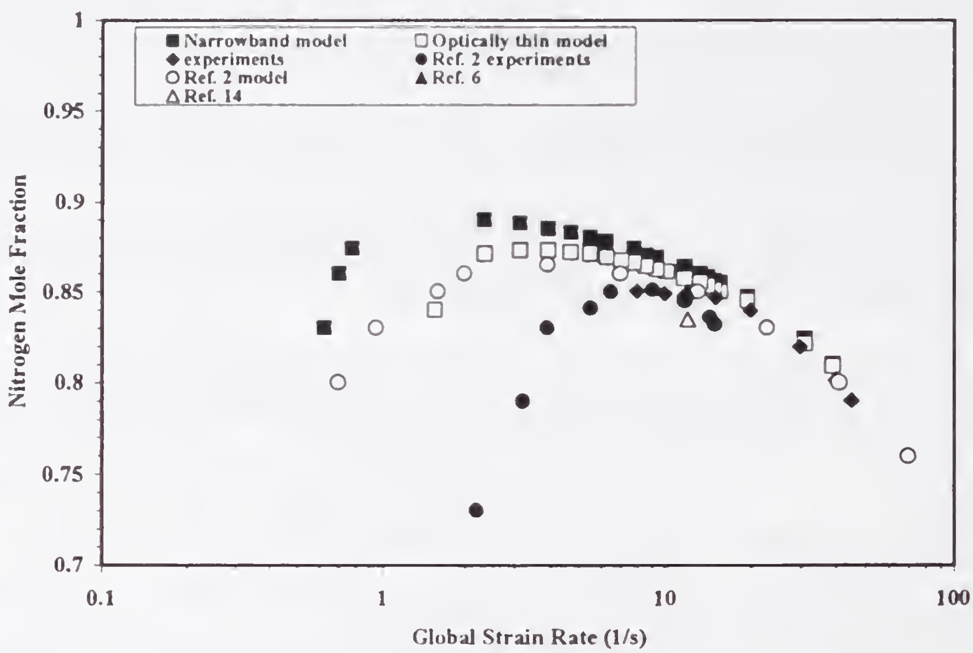

Figure 2. Comparison of measurements and simulations of the critical mole fraction of N_2 in the fuel stream of methane-air diffusion flames.

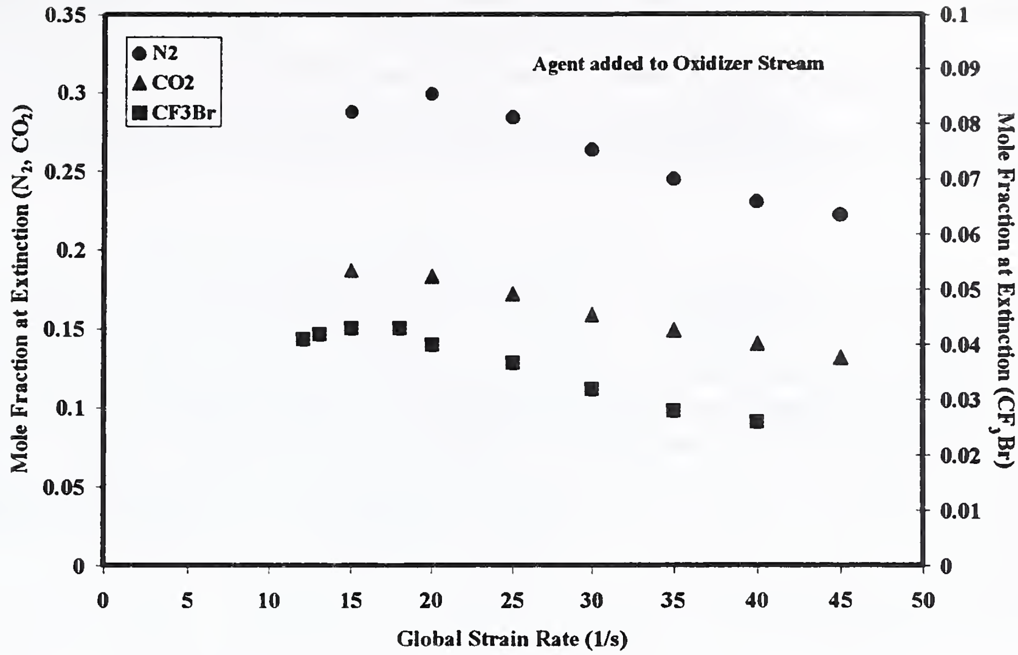

Figure 3. Measurement of the critical mole fraction of N_2, CO_2, and CF_3Br in the oxidizer stream of methane-air diffusion flames.

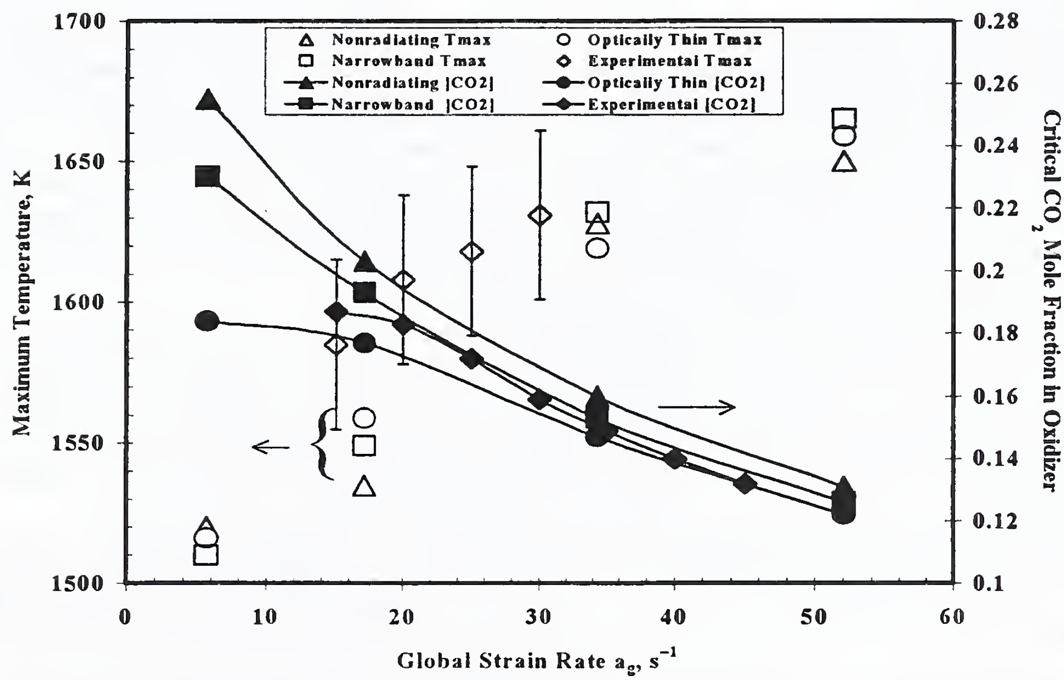

Figure 4. Comparison of measurements and simulations of the peak flame temperature and the critical mole fraction of CO_2 in methane-air diffusion flames with CO_2 added to the oxidizer stream.

NUMERICAL MODELLING OF FIRE AND GASEOUS FIRE SUPPRESSION

T.Tsuruda*, D.Makarov**

* ***National Research Institute of Fire and Disaster (Japan),*** *14-1, Nakahara 3-chome, Mitaka, Tokyo 181, Japan*

*****All-Russian Research Institute for Fire Protection,*** *VNIIPO-12, Balashiha-3, Moscow region, 143900 Russia*

Abstract

This paper describes the CFD approach to the problem of design and optimisation of a gaseous suppressant injection system. Different ways of suppressant injection, applied for the same scenario of a real fire extinguishing experiment, were studied. The suppressant distribution effectiveness for three suppressant injection methods was studied with the use of specially constructed numerical parameter, which can be obtained from a CFD model. The analysis of the fire suppression and suppressant distribution proves that the most uniform suppressant distribution provides the most quick and reliable fire suppression. It is shown that the suppressant distribution doesn't differ significantly between the cases of isothermal and fire injection conditions. Hence, the practical design and optimisation of suppressant injection systems can be based on the numerical simulation of isothermal suppressant propagation without fire modelling.

Introduction

In the current time, the modelling of fire related phenomena becomes a significant part of fire safety engineering. It is especially important for design of new types of buildings and compartments, or not-standard facilities, where the implementation of performance-based fire regulation is needed.

Gaseous fire suppression systems are flexible for design, easy and cost-effective for maintenance. At the moment, the design of these systems is based on the traditional analytical model, which imposes the perfect isothermal suppressant mixing and the uniform suppressant distribution without regard to the construction of suppressant injection system [1].

The results of Computational Fluid Dynamics (CFD) modelling of a gaseous fire suppression [2] shows that the conditions of gaseous suppressant injection and propagation are far from the assumptions of the analytical model and fire can continue much longer than it can be expected from the analytical solution.

For the CFD approach to the gaseous fire suppression, the extinguishing model is necessary. An experimentally based extinguishing model, reported in [3], was used for the fire suppression with a dry aerosol. The model uses the flame extinguishing concentration of suppressant as the criterion of fire extinguishing. The flame extinguishing concentration for a considered suppressant and a fire load can be easily obtained from literature or experiment with high precision[2].

In this research, the fire suppression effectiveness is studied for different suppressant injection systems. The method of evaluation a suppressant distribution effectiveness is developed and demonstrated.

The Problem Formulation

At the moment, we assume that an effective gaseous fire suppression must provide uniform suppressant distribution. The real, non-uniform suppressant distribution can be obtained

from a CFD solution, though it is difficult to evaluate the uniformity of a suppressant distribution from three-dimensional raw data.

For this propose, the use of some characteristic parameter, which reflects the suppressant distribution uniformity as one, single value, must be the most profitable.

The mentioned above parameter can be considered as follows [4]:

$$I = \frac{1}{M_{cmp}} \int_{V_{cmp}} \left(1 - \left|Y_{spr} - Y_{spr,u}\right|\right) \rho \, dV . \tag{1}$$

The worst case of suppressant distribution, when suppressant is not distributed at all, is shown schematically in Figure 1; the whole suppressant amount is concentrated in one part of compartment, $Y_{spr} = 1.0$, while the other part is empty, $Y_{spr} = 0$. The following expression for the proposed parameter I can be obtained in this case:

$$I_* = \left(1 - Y_{spr,u}\right)^2 + Y_{spr,u}^2 . \tag{2}$$

We can normalise the proposed parameter, using the value I_*,

$$I_m = \frac{I - I_*}{1 - I_*} . \tag{3}$$

The normalised parameter I_m changes its' value between zero (in the worst case of non-distributed suppressant) and unity (for this ideal case of uniformly distributed suppressant). Now, the uniformity of any suppressant distribution can be represented as a one, single value of the parameter I_m, which has clear physical meaning.

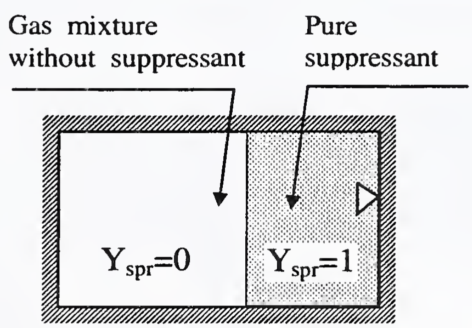

Figure 1. Calculation scheme of non-distributed suppressant

Modelling of Fire and Fire suppression

Calculation Domain and Fire Extinguishing Scenario

The fire scenario of the real fire extinguishing experiment in a garage compartment, which was held by the Science University of Tokyo, was used in this research. The description of

fire modelling will be skipped in this paper and the attention will be paid only for the modelling of fire extinguishing.

The clear forced convection type of flow existed inside of garage during the period of suppressant discharge. It allowed the use of a small calculation domain, consisted only of garage compartment without free regions, to overcome the problem of unacceptable loss of computer resources. The calculation domain is shown in Figure 2. The garage itself and internal layout (car parking construction and two cars, installed in it) were modelled. The numerical grid consisted of 29, 33 and 46 grid nodes along width, length and height of garage correspondingly (44,022 grid nodes in total). At the preliminary stage of fire, the door and the window were opened. Before the discharge, all openings were shut and the gas mixture left the garage through the pressure release valve, installed near the door. In the numerical simulation, it was assumed that the kerosene pool fire served as a source of the whole Heat Release Rate (HRR). The fuel mass flow rate of kerosene was estimated as follows:

$$\tau \leq 320\,\mathrm{s} \quad \dot{m}_{fl} = 9.93 \times 10^{-7}\,\tau \ \ \mathrm{kg/s}, \qquad \tau > 320\,\mathrm{s} \quad \dot{m}_{fl} = 12.42 \times 10^{-6}(\tau - 294.4) \ \ \mathrm{kg/s}.$$

The inert gaseous suppressant IG541 [5] was used in experiment. The suppressant was discharged in the period $520 < \tau < 624$ s. The suppressant mass amount was $M_{spr} = 128.5$ kg, which corresponds to the mean mass flow rate of suppressant $\dot{m}_{spr} = 1.23$ kg/s.

In the experiment, the suppressant was injected through the nozzle, which distributed suppressant in a radial direction. In the modelling, three different suppressant injection methods were used:

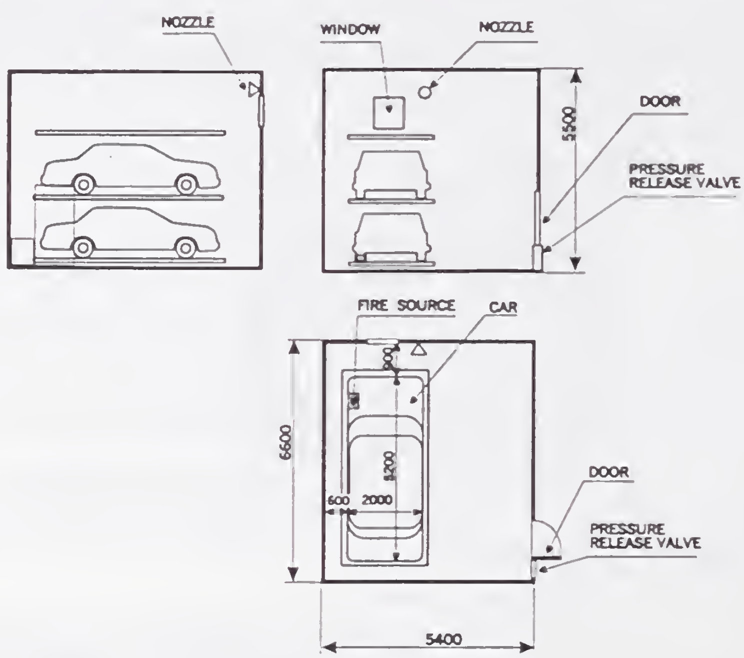

Figure 2. Calculation domain

1) the experiment case - a radial spreading flow, which distributed the suppressant along the wall and ceiling;
2) the one nozzle flow, forming a straight suppressant jet flow, directed at the opposite wall. The initial velocity of suppressant jet is $u = 55.7$ m/s;
3) the three nozzle flow, formed by three similar nozzles at different garage levels. The initial velocity of every jet flow is $u = 18.6$ m/s in this case.

All three methods of the suppressant injection are shown schematically in Figure 3 (a, b and c). The injection nozzles were positioned on the opposite wall in the second and third cases, to prevent an excessive leakage of suppressant jet to the pressure release valve.

Mathematical Model

The mathematical model, used for the fire and fire extinguishing simulation, was formed by the following three-dimensional governing equations:

- mass conservation equation,
- momentum conservation equations,
- energy conservation equation,
- conservation equations for species (Y_{ox}, Y_{fl}, Y_{spr}),
- equations for k-ε turbulence model of Launder-Spalding, adapted for naturally convected flows [6].

The combustion was modelled with Eddy Break-Up model [7]. Radiation heat transfer was taken into account as a heat sink term (the fraction of the total heat release rate, lost due to radiation, was taken as χ=0.3).

The control-volume based finite-difference method [8] was used to solve the described above mathematical model.

The extinguishing model [3] was applied for the fire suppression modelling. The model prescribes zero fuel consumption rate S_{fl}, when the local suppressant concentration Y_{spr} is higher than the flame extinguishing concentration of a suppressant Y^*_{spr}:

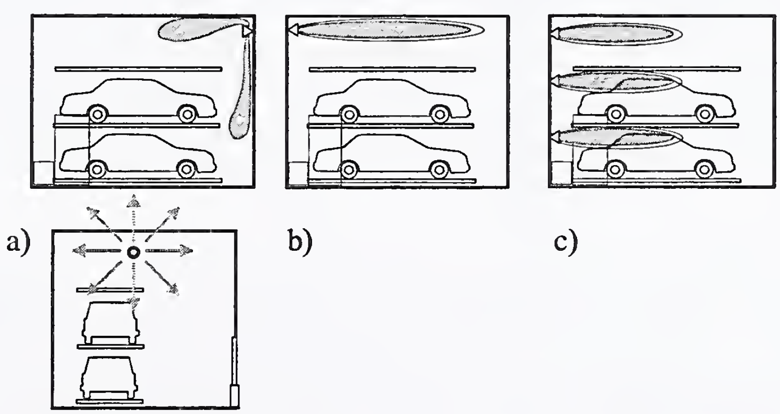

Figure 3. Different methods of the suppressant injection

$$S_{fl} = 0 \quad \text{when} \quad Y_{spr} \geq Y^*_{spr}.$$

In this research, the volume flame extinguishing concentration of IG541 for kerosene $v^*_{spr} = 0.31$ [9] was used for the fire suppression modelling since the flame extinguishing concentrations for car materials were unknown.

Boundary Conditions

The boundary conditions at inflow assumed the constant mass flow rate of suppressant over the whole period of injection ($Y_{spr} = 1.0$, $\dot{m}_{spr} = 1.23$ kg/s). The outflow boundary conditions were set for all variables at the pressure release valve, where the boundary velocities were obtained from the assumption of equal mass fluxes at inflow and outflow, $\dot{m}_{spr} = \dot{m}_{out}$. All obstacles were assumed adiabatic and impermeable. To solve the conservation equations of the k-ε turbulence model, the turbulence level of ambient atmosphere was set to 5% and an ambient atmosphere viscosity was $\mu_t = 10^{-4}$ Pa·s. The initial distributions of dependant variables for the time $\tau = 520$ s were taken from the solution of the previous stage of the fire ($0 < \tau \leq 520$ s).

Results of Fire Suppression Modelling

Heat Release Rate

The Heat Release Rate (HRR) behaviour with time must be the most interesting result of the fire extinguishing modelling. The HRR for all injection cases is shown in Figure 4.

It needs to notice that a HRR can not be helpful for evaluation of the fire extinguishing system. The HRR depends on the peculiar fire source position and it can possess a quite different behaviour for another position of fire source. Nevertheless, the comparison of different injection methods on the base of modelled HRR values can be voluble.

It is seen that the fire was suppressed in all three injection cases during simulation. It is also interesting, that the fire suppression process is time dependent, which is impossible to reproduce, using the analytical model.

Though the radial spreading flow shows the earliest time of extinguishing beginning, at $\tau = 575$ s, the fire suppression occupies the longest time and the extinguishing is very unstable. Otherwise, the decrease of HRR, delivered with the one-nozzle and three-nozzle flows, is very quick and sharp. Although for the three-nozzle flow, the extinguishing begins later, it finishes in the same time as for the one-nozzle flow. This fact of different HRR behaviour must have explanation in the terms of the suppressant distribution over the compartment.

Parameter I_m

The results for the proposed parameter I_m with time are shown on the Figure 5. Let us be reminded that the value $I_m = 1.0$ corresponds to the absolutely uniform suppressant distribution.

It is interesting to see that the all suppressant injection systems provided almost the uniform suppressant distribution at $\tau = 624$ s and the value of the parameter I_m, during the most part of injection, is different for all of them and the suppressant distribution is far from uniform.

The one-nozzle flow demonstrates the most uniform suppressant distribution during the whole period of injection. The three-nozzle flow provides the value of I_m, which is very close to the same in the one-nozzle case. It means that for the both injection methods, the suppressant distribution uniformity doesn't differ significantly. This must be the reason for the same early moment of fire extinguishing for these methods. The radial injection demonstrates the least uniform suppressant distribution, and it is clearly reflected in the characteristic behaviour of the fire extinguishing, which goes very long time and unstable at some period.

Hence, we can conclude, the proposed parameter really reflects the effectiveness of the fire suppression system and can be used in practice for the design optimisation of the injection system or an objective comparison of different injection methods.

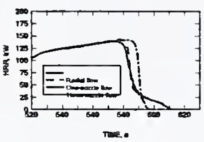

Figure 4. Heat Release Rate

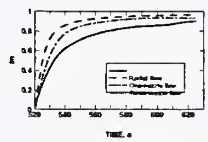

Figure 5. Distribution parameter I_m

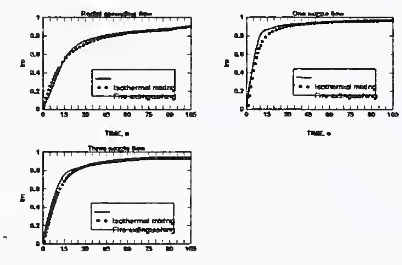

Figure 6. Comparison of suppressant injection under the isothermal and fire conditions

The amount of the suppressant, provided by all injection systems, are almost the same (95.4, 97.1 and 94.9 kg for radial spreading, one-nozzle and three-nozzle flows respectively). So, in this research the mass of suppressant, which is left in the compartment after extinguishing, can be eliminated from the analysis of the fire suppression effectiveness.

Results of Isothermal Injection Modelling

It is evidently, that the same distribution parameter I_m can be easily obtained for the isothermal injection conditions, without fire modelling. The mathematical model for this problem formulation is much simpler, because the less number of equations need to be solved now and the absence of temperature distribution provides a faster convergence in a numerical simulation.

For the modelling of the suppressant injection under isothermal conditions, the initial velocity was equal to zero all over the compartment and the compartment was assumed filled with air. The results of the isothermal injection modelling, in comparison with the modelling of the fire suppression, are presented in Figure 6 a, b, c for the radial spreading, one-nozzle and three nozzle flows respectively.

From these comparison it is clearly seen that generally there is no significant difference between suppressant distributions in the case of fire, where the initial temperature and velocity

fields existed inside of compartment, and for the case of isothermal conditions. Some discrepancy in the suppressant distribution occurs during the early period of the suppressant injection. After the initial stage of injection, this difference disappears as the flow inside of compartment is controlled by the strong, forced-convected flow of suppressant.

Conclusion

In this research the investigation of the gaseous suppressant distribution effectiveness was made with the help of the CFD technique.

The results of the suppressant injection and the fire modelling demonstrated that the effectiveness of fire suppression is closely linked with the effectiveness of suppressant distribution.

The parameter I_m for the evaluation of suppressant distribution uniformity was proposed.

The analysis for the Heat Release Rate and the parameter I_m proves that the most effective and uniform suppressant distribution provides the most effective fire suppression. From this we conclude that the proposed parameter I_m can be used as the tool for design and optimisation of gaseous extinguishing systems.

The comparison of the suppressant discharge under fire conditions and for isothermal case shows that the initial naturally convected flow field and the initial temperature distribution don't play significant role for the suppressant distribution in the case of fire.

Hence, the evaluation of the gaseous fire suppression system effectiveness can be obtained from the reasonably simplified convection-diffusion CFD simulation without fire model, which makes the usage of the proposed evaluation method very simple and available for practical applications.

Nomenclature

I	Parameter for suppressant distribution uniformity (--)
I_m	Normalised parameter for suppressant distribution uniformity (--)
I_*	Parameter for non-distributed suppressant (--)
M	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
S_{fl}	Fuel mass consumption rate (kg/m^3/s)
V	Volume (m^3)
Y	Mass concentration (--)
ν	Volume concentration (--)
μ_t	Turbulent viscosity (Pa·s)
ρ	Density (kg/m^3)
τ	Time (s)
Superscript	
•	flame extinguishing
Subscript	
cmp	compartment
fl	fuel
ox	oxygen
out	at outflow from calculation domain

spr	suppressant
u	uniform

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Fire Extinguishing Effect of Water Vapor

Yoshio Ogawa

National Research Institute of Fire and Disaster
Fire and Disaster Management Agency, Ministry of Home Affairs
14-1, Nakahara 3-Chome, Mitaka, Tokyo 181-8633, JAPAN

Abstract

Flame extinguishing effect of water vapor for premixed flame was investigated using tubular flame burner method. Extinction limits for methane-air-water vapor mixture were estimated by calculating adiabatic flame temperature as the effect of water vapor was the same as inert gases. The estimated flame extinguishing effect of water vapor was more than that of nitrogen and less than carbon dioxide. The extinction limit was compared with observed extinction limit for the mixture with added 10 percent of water vapor and inert gas. The observed data showed that the estimated effect of water vapor was slightly underestimated.

1. Introduction

After prohibition of the production of the halon fire-extinguishing agents, several types of new agents have been developed to date as halon replacements, and the current agents are also noticed as candidate [1-2]. Water is one of the considerable options for halon replacements, and it has been investigated and applied to fire-extinguishing systems as sprinkler, water mist and so on. Some of fire extinguishing effect of water based systems are considered as high latent heat of evaporation. After evaporation, water will act as water vapor, hence it need to investigate the fire extinguishing efficiency of water vapor. In ambient condition, it was investigated that the fire extinguishing efficiency of water vapor for diffusion flame and premixed flame using cup burner method and tubular flame burner method, respectively [3-4], however water vapor can be mixed only 3 percent into ambient air because of saturated vapor pressure of water is only 3 kPa under 25 °C and atmospheric pressure.

In this study, estimation of extinction limit of methane-air mixture containing water vapor was carried out by calculation of adiabatic flame temperature at the extinction limit measured by the tubular flame burner method. To confirm the estimated fire extinguishing efficiency of water vapor, the measurements of extinction limits of methane-air mixture added with water vapor under elevated temperature were performed using tubular flame burner method.

2. Experimental

A tubular flame burner system [5-7] was used for measurement of the extinction limits. Figure 1 is a schematic diagram of the apparatus. The system consists of two parts. One is the tubular flame burner and the other is a gas mixture supply unit. The tubular flame burner consists of a porous bronze cylinder. The dimensions of the burner are 30 mm in inner diameter, 80 mm in length, 5 mm in thickness, and 5 μm in porosity. To prevent the burner heating by the flame, it was equipped with water-cooled ends of 25 mm in length, and nitrogen injection parts of 25 mm in length at both sides as shown in Fig. 1.

Methane with purity of more than 99.9 percent by volume was used as fuel. Dry air is supplied from an air compressor equipped with dryer. Carbon dioxide (CO_2) and nitrogen (N_2) are used as agent, and their purity were more than 99 percent by volume. Water vapor was generated by evaporation of commercial distilled water through high temperature heater. The flow rate of water vapor was calculated from water weight supplied to the heater. The flow rates of gases were adjusted freely by the precision-type mass flow controllers, then they were

mixed. Temperature of mixture was kept above 70 °C from heater to burner.

The mass flow controllers calibrated by wet gas meters, and the maximum relative errors of the flow rate are estimated within plus or minus 1 percent. It is expected that the extinction limit concentrations measured by this system include an experimental error of less than 3 percent.

Since a set-up angle of the burner and injection velocity of the gas mixture affect the extinction limits, such effects were investigated to decide the experimental conditions. Here, the injection velocity stands for average flow velocity at the porous cylinder surface of the burner, calculated by dividing the mixture flow rate by the area of the surface. To obtain much wider extinction limits in this burner, the set-up angle of the burner and the injection velocity of mixture from burner surface were chosen as horizontal and 50 mm/s, respectively [6].

3. Estimation of extinction limit of water vapor mixture by calculation of adiabatic flame temperature at extinction

It was reported that the adiabatic flame temperature calculated for fuel-air-inert gas mixture at the extinction limits was the same to the temperature for other inert gas mixture in case of that the equivalence ratio of fuel to oxygen was constant [8], and the fire extinguishing effect of water vapor was almost the same as the effect of inert gases [9]. Here the extinction limit of the mixture with added water vapor was estimated by calculating the adiabatic flame temperature of the mixture at extinction.

The adiabatic flame temperatures were calculated for the methane-air-agent mixtures at the condition of the extinction limits. A previously developed code was used for the calculation [10]. The calculations were carried out taking dissociation fully into account. The calculation of mixture composition containing water vapor was continued until the temperature difference between water vapor mixture and the mixture with added nitrogen or carbon dioxide at the same equivalence ratio was reduced within 5 K.

4. Results and Discussions

4.1 Mixture temperature and extinction limit of methane-air-carbon dioxide mixture

Temperature effect of mixture for flammability limit is discussed in following equations [11],

$$L_t/L_{25}=1-7.21\times10^{-4}(t-25) \qquad (1)$$

$$U_t/U_{25}=1+7.21\times10^{-4}(t-25) \qquad (2)$$

L_{25} and U_{25} are lower and upper flammability limits of mixture temperature at 25 °C, respectively. L_t and U_t are also lower and upper limits at t °C, respectively. In case of mixture temperature at 70 °C, answers of equations (1) and (2) are,

$$L_t/L_{25}=0.97$$

and

$$U_t/U_{25}=1.03$$

It shows that lower and upper flammability limits are both expanded to 3 percent relatively since the temperature of mixture is elevated until 70 °C. These expansion of flammability limits are the same degree as the experimental error of this burner system, therefore there expects small difference on flammability limits between under 25 °C and 70 °C.

To verify above expectation, the extinction limits were measured for 70 °C of methane-

air-carbon dioxide mixture. Result is shown in Fig. 2. The ordinate represents agent mixture concentration and the abscissa shows fuel concentration. There are no difference between the extinction limits at 25 °C and 70 °C.

4.2 Estimated extinction limit of methane-air mixture containing water vapor

Through the calculation of the adiabatic flame temperature for methane-air mixture with added agent, the flammable region of methane-air-water vapor mixture was obtained as shown in Fig. 3. The peak concentration of water vapor was 35.8 percent by volume. The peak concentration of carbon dioxide and nitrogen were 29.6 and 41.7 percent by volume, then in order for high efficiency, the agents were lined up as carbon dioxide, water vapor, and nitrogen.

4.3 Extinction limits of methane-air mixtures with added water vapor and inert gas

To investigate fire extinguishing effect of water vapor, the extinction limits of methane-air mixture with added agent were measured under 70 °C. The agents were carbon dioxide-water vapor mixture and nitrogen-water vapor mixture. Each methane-air-agent mixture contains 10 % of water vapor except upper and lower limits without agent. Figure 4(a) shows the measured and the calculated result for carbon dioxide-water vapor mixture. To calculate the extinction limits of mixture containing 10 % of water vapor, following equation was used [8],

$$\frac{1}{C}=\sum_{j=1}^{n}\frac{Xj}{Cj} \qquad (3)$$

Here, C is the concentration at extinction limit of inert gas-water vapor mixture, Xj is mole fraction of j th component in the mixed agent, and Cj is the concentration of j th component as the pure agent under the condition of the constant equivalence ratio. As compared with both limits in Fig. 4(a), the calculated results were larger than the measured extinction limits. The peak concentrations of the measured and the calculated were 28.3 percent and 30.8 percent, respectively.

As shown in Fig. 4(b), the measured result for nitrogen with 10 % water vapor was similar to the calculated for the fire extinguishing efficiency. The peak concentrations of the measured and the calculated were 38.5 percent and 39.7 percent, respectively. They show that the fire extinguishing efficiency of water vapor estimated by calculation for the adiabatic flame temperature was underestimated.

5. Conclusion

The estimated flame extinguishing effect of water vapor was obtained as provisional index through the calculation, and was more than the effect of nitrogen and less than carbon dioxide. The extinction limit was compared with observed extinction limit for the mixture with added 10 percent of water vapor and inert gas. The observed data showed that the estimated effect of water vapor was slightly underestimated.

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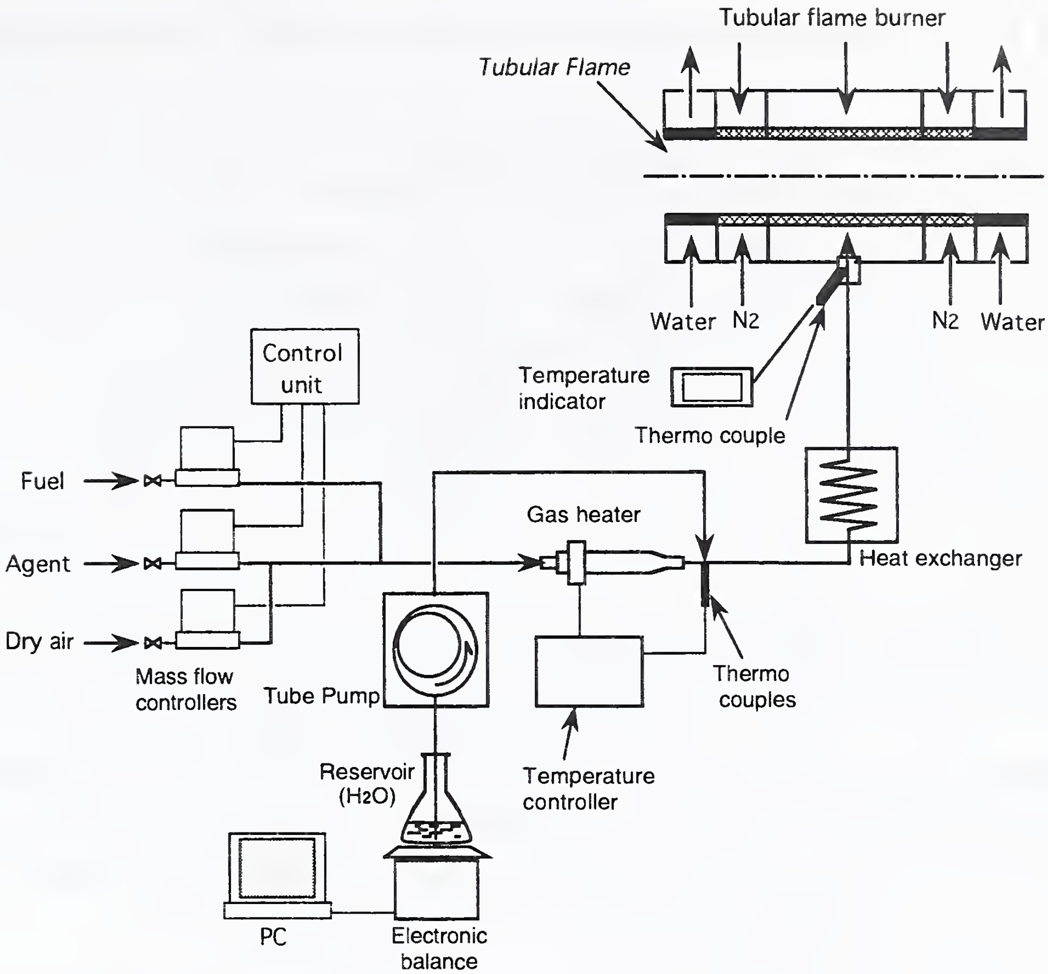


Fig. 1 Experimental apparatus

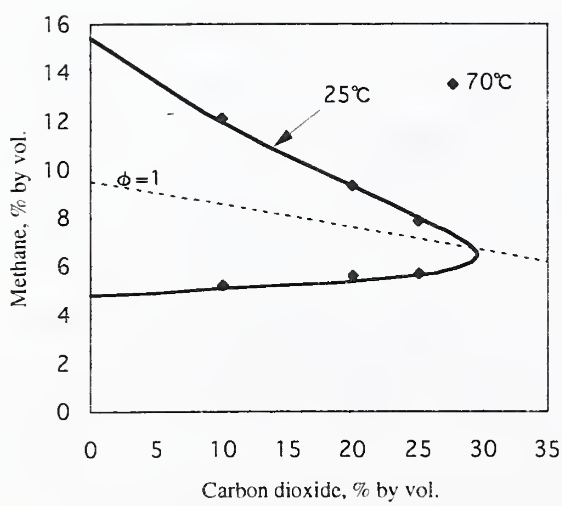


Fig. 2 Extinction limits of methane-air-carbon dioxide mixture under 25℃ and 70℃

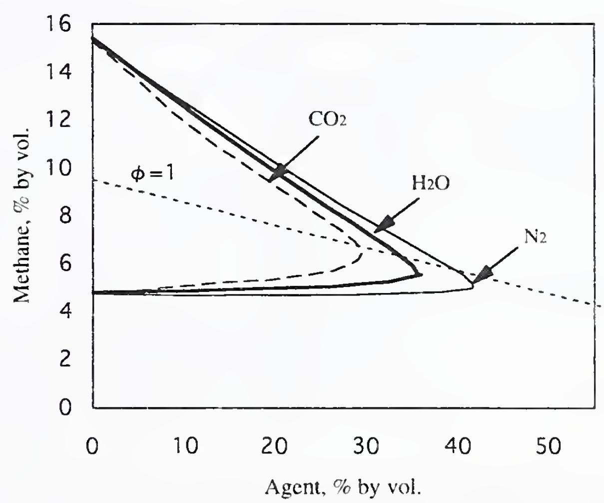
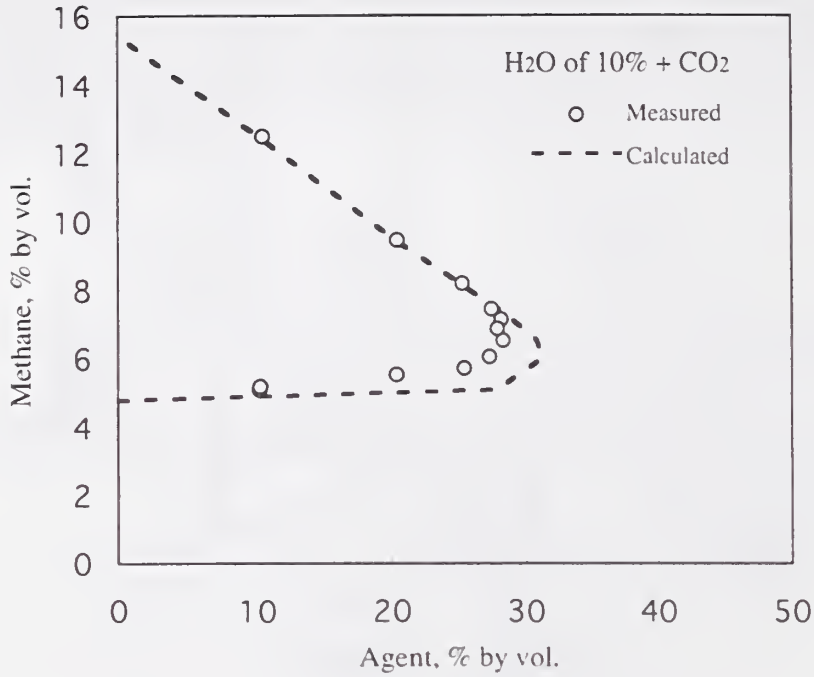
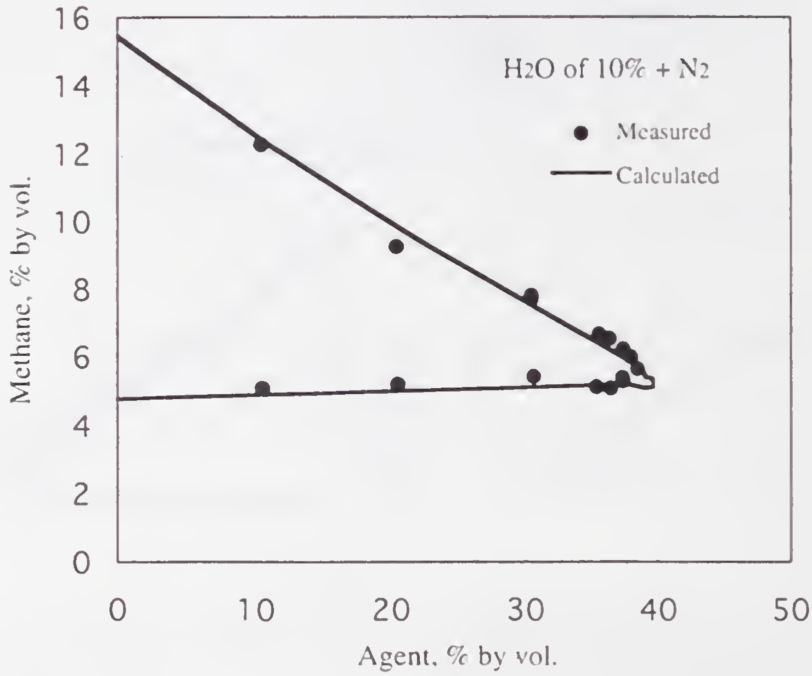


Fig. 3 Estimated extinction limit of methane-air-water vapor mixture from calculation of adiabatic flame temperature



(a)



(b)

Fig. 4 Extinction limits of methane-air mixture added with water vapor and inert gas ((a)water vapor & CO_2, (b)water vapor & N_2)

Suppression Mechanism of Water Mist for Pool Fire

Masahiro Morita
Science University of Tokyo
1-3 Kagurazaka , Shinjyuku-ku , Tokyo 162-0825 , Japan
Tatsuya Minami , Akimitsu Kikkawa
Akifumi Kubota , Hirotoshi Megumi , Hiroaki Suzuki
Center for Research & Development , Yamato Protec Corporation
1951,Nagasao-Dohmae , Kawachi-Machi , Ibaraki , 300-1312 , Japan

ABSTRACT

Suppression mechanisms of water mist for pool fire has been studied for these years.
The purpose of this paper is to conduct the effect of latent heat by water mist compared with that of inert gas against n-heptane fire in a compartment.
The droplets of water mist are in the range of 85 μ m measured by saunter mean diameters.
The relationship of the effect between latent heat and heat capacity under the condition of diluted oxygen. The cooling of fuel has also been discussed.

1. INTRODUCTION

Water vapor is known as a kind of an inert gas for suppression of fire. [1] Water mist is one of good measures of changing water to inert gas for fire suppression agent. Studies on water mist have been conducted from the points of suppression agent against fire for these years by many researchers. [2,3,4]However, water vapor only exists under the condition of physical balance with saturation pressure of water depending atmospheric temperatures.
If a fire in a compartment is large enough compared to the volume of the room, the heat released by the fire will produce sufficient amount of water vapor. However, if the fire is small, evaporated water is small taking the role of cooling room temperatures.
Physical balance between water and vapor make the agent uncertain as a suppressant against fires.

In the present work, the effect of the latent heat has been discussed relating to the relationship between heat capacity and concentration of oxygen for various water flow rate with n-heptane oil fire.

2. EXPERIMENTS

Figure 1 shows the outline of the experimental apparatus. The air flow in the compartment, whose dimensions are 3m long, 3m wide and 2.5m high is controlled by ventilators. The oxygen concentration in the compartment was controlled by discharging nitrogen and air. The oil pan was placed in the center of the floor. Full-cone type nozzles were used. The mean value of droplets were 85 microns in diameter at 0.7MPa measured by Phase Doppler Particle Analyzer (PDPA). The nozzles were set under the ceiling shown in figure 1. The nozzles were located at 2.2m high from the floor level. and the mist were sprayed out into the fire source of oil-pan. The water vapor concentration was calculated from saturated vapor pressure of water at various room temperatures. The concentration of O_2, CO and CO_2 gases were collected at the point of the 80cm apart from the heat source and 50cm above the floor. Vapor and drains were removed prier to measuring O_2, CO and CO_2 gases. The real gas concentrations of O_2, CO and CO_2, were amended by reducing actual water vapor concentration from measured gas concentration

The water mist was discharged when flame temperatures at some points above the center of heat source become nearly steady. The extinguishing time was taken as the duration between initiation of discharging and extinguishment of fire. Complete extinguishment of fire was defined as re-ignition of the remained oil does not catch fire within one minute.

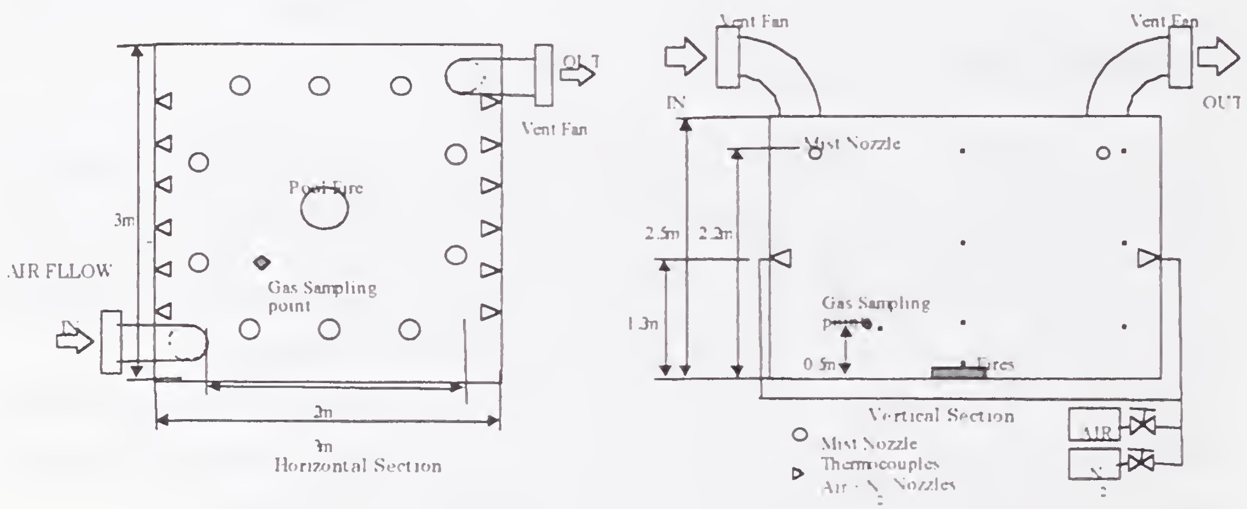


Fig 1. Test Compartment and location of devices.

3. RESULTS and DISCUSSIONS

Figuer2 shows the time-temperature curves of oil fires at the point of 110mm above the heat source pan. The rates of supplying water at the area of the fire source (denoted the flow-rate of water mist) were 0.2 L/m^2/min, 0.4 L/m^2/min, 1.1 L/m^2/min, 1.5 L/m^2/min, respectively and mean droplet size was about 85 μ m in diameter. The flame temperatures show the decayed oscillating phenomena succeeding the fire to be extinguished by water mist. The delayed curves are related to increasing rate of water flow.

Figure 3 shows the relationship between the flow rate of water mist and fuel surface temperatures.The more flow rate of water mist, the fuel surface temperatures become quickly lower. When temperatures reach 60℃, flames are disappeared at any flow rate of water mist.

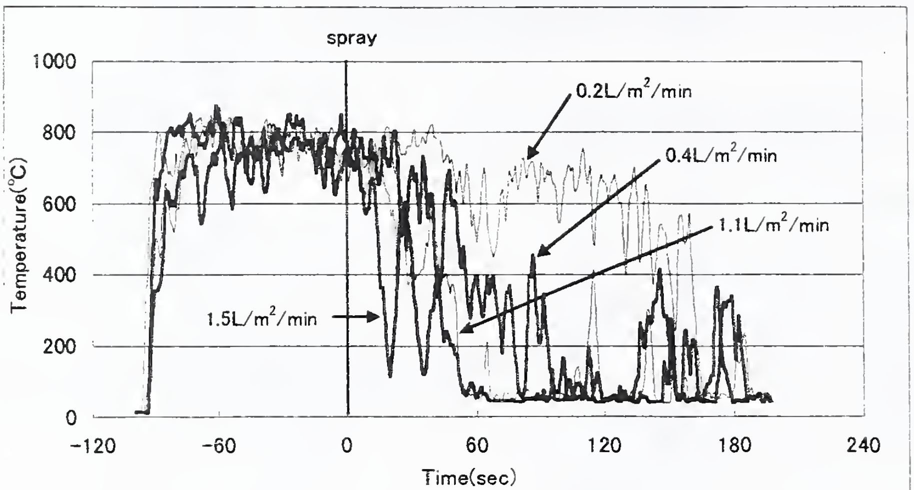


Fig 2 Flame Temperatures

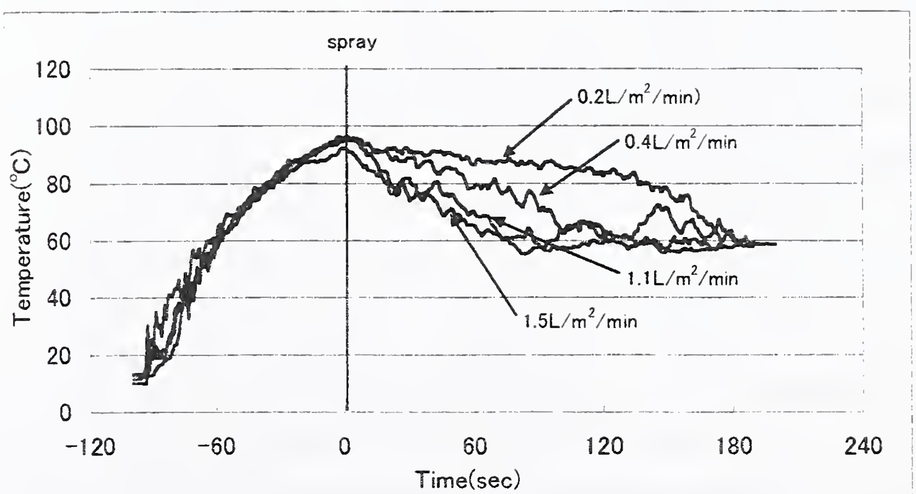


Fig 3 Fuel Surface Temperatures

Flame extinguishing concentrations of inert gases are shown in table 1.[5 , 6] This is known as the difference is due to the heat capacity of each gas for extinguishing flame. Figure 4 shows the relationship between the oxygen concentration and the heat capacity (at 1500K). This suggests that there is a linear relationship between oxygen concentration and the heat capacity for flame extinction by inert gases.

Table1 Flame Extinguishing Concentrations (%) against n-Heptane Fire [5 , 6]

Inert gas	*Flame extinguishing concentration*
CO_2	22%
N_2	33.6%
Ar	43.3%
H_20	(26%)

H_20 : calculated value assuming 1860K for adiabatic flame temperature

Table2 Heat Capacity of Inert Gases at 1500K

Inert gas	*J mol K*
CO_2	58.38
N_2	34 86
Ar	20.79
H_20	46 98
Air	35 66

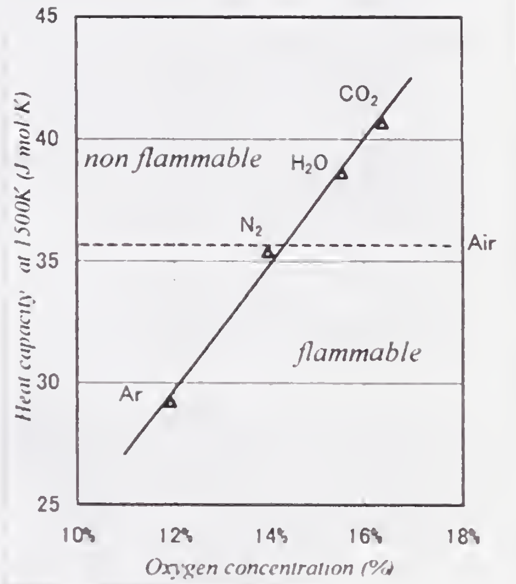


Fig4 The Relationship between Oxygen Concentration and Heat Capacity for Inert Gases

Figure 5 shows the results of water mists tests. The relationship between the real oxygen concentration and the difference of heat capacity as compared to air are shown in Figure 5. The increase of heat capacity is due to the production of water vapor and CO_2. The difference of heat capacity is the difference between heat capacity of air and calculated heat capacity of measured gases, which are water vapor, carbon dioxide, oxygen and nitrogen. In these tests, measured concentration of carbon dioxide and water vapor were 1.2～1.9% and 6～14%,respectively. Therefore, the increase of heat capacity is almost due to water vapor.

The oxygen dilution is due to consumption by combustion and replacement by water vapor and discharged nitrogen. The plotted points show the results extinguished and non-extinguished fires at the conditions. The dotted line shows threshold of extinguished and non-extinguished by water mist. The real line shows flaming limit under the existence of inert gas. This is the same shown in figure 4. This suggests that the difference between the line of flaming limit under the existence of inert gas and extinguishment by water mist is due to

increasing flow rate of water. Since the relationship between large heat capacity and oxygen dilution is a mechanism of suppression effect as inert gas. This suggests that the differences between the result of water mist tests and flaming limits under the existence of inert gas are due to latent heat.

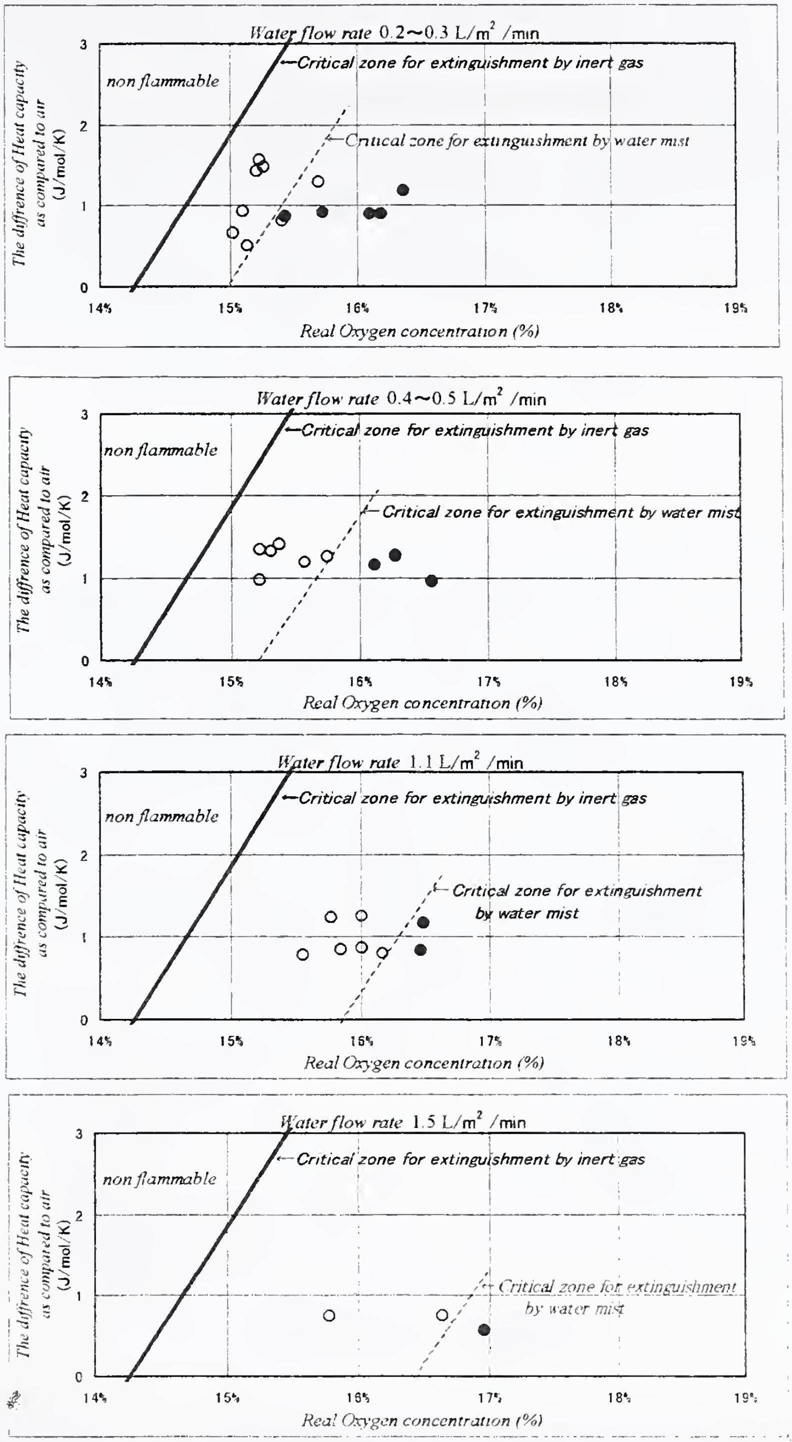


Fig5 The relationship between real oxygen concentration and the difference of heat capacity as compared to air

○ extinguished
● not extinguished

Figure 6 shows the difference of heat capacity and oxygen concentration related to the water mist tests result and flaming limit under the existence of inert gases. The line suggests the effect of latent heat. When water flow rate is 0.2～0.5 $L/m^2/min$, the value of latent heat effect is about the same one of the heat capacity by water vapor. If water flow rate becomes 1.1 $L/m^2/min$, the value of latent heat effect becomes about 2～3 times bigger than that of the heat capacity by water vapor and water flow rate becomes 1.5 $L/m^2/min$, then the value of latent heat effect becomes about 3～6 times bigger than that of the heat capacity by water vapor.

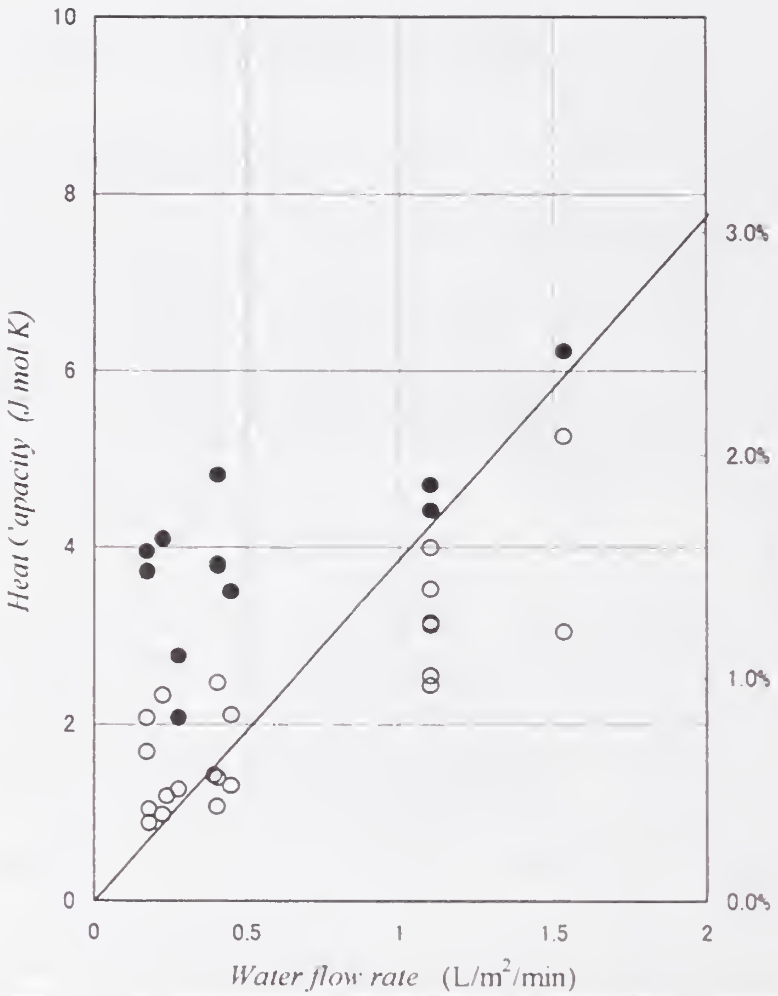


Fig 6 The relation ship between flow rate of water mist tests results and flaming limits under the existence of inert gas in Fig 5

○ *extinguished*
● *not extinguished*

4. CONCLUSION

The effect of latent heat was studied by comparing to flaming zone by inert gases. The suppression factor of pool fire by water mist involves four items, which are latent heat of vaporization, larger heat capacity, oxygen concentration and cooling of fuel. Factor of cooling of fuel seems very small compared to other three factors. Since the relationship between heat capacity and oxygen concentration may take nearly the same effect as that of inert gases.

As the results, the effect of latent heat for various water flow rate were studied. The effect of the latent heat, which increase with water flow rates, is bigger than that of heat capacity which is not big change by water flow rates.

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Understanding Sprinkler Sprays: Trajectory Analysis

DAVID T. SHEPPARD and PRAVINRAY D. GANDHI, Ph.D.
Underwriters Laboratories, Inc.
Northbrook, IL USA

RICHARD M. LUEPTOW, Sc.D.
Northwestern University
Evanston, IL USA

1 Abstract

Previous research on the characterization of sprinkler water spray has concentrated on understanding the droplet and velocity size distributions. However, previous research appears not have used the droplet and velocity distributions to determine the delivered density of water at a specific distance below the sprinkler, and thus the results, while interesting, do not provide an analysis of the local delivered density. This is an important factor in control and suppression of fires.

In this paper, an analytical trajectory analysis is combined with the results of experiments conducted with a laser measurement technique called Particle Image Velocimetry (PIV). The trajectory analysis is used to predict the path of individual droplets. Particle Image Velocimetry (PIV) is used to develop a description of the droplet velocities and water densities leaving the sprinkler.

The trajectory analysis provided several insights into the physics of sprinkler sprays. For example, it was found that larger droplets always travel farther horizontally from the sprinkler than smaller droplets. This phenomena is caused by the momentum of larger droplets being proportionally larger than the drag force.

The experimental study has shown that the droplet velocities and water fluxes are different at different angles from the sprinkler. It was found that, for the sprinkler studied, the droplet velocities could be characterized as a purely radial flow at a radial distance ranging from 175 to 300 mm depending on the sprinkler. Further, it was also found that the angular dependence of the spray characteristics produce different delivered water densities and that the sprinkler sprays can not be characterized as axisymmetric flows.

The combination of the trajectory analysis and the experimental study was used to predict the water density measured in the traditional pan distribution tests. The results of this comparison provided good preliminary results. Further refinement of the analysis and experimental techniques will be required to provide acceptable engineering results.

2 Measurement Techniques

2.1 Sprinkler Spray Characterization Experiments

Particle Image Velocimetry (PIV) is used for characterizing the sprinkler spray velocity distributions and water fluxes. In PIV a sheet of high-intensity laser light is positioned within the flow field. A video camera is aligned perpendicular to the laser sheet so that it can image the droplets when they are illuminated by a flash of laser light that is only a few nanoseconds long as shown in Figure 1. Using a sequential pair of images of droplets, the statistical average of the displacement of many droplets in the same region of the imaged velocity field is determined using Fourier-based cross-correlation methods. In this way, a grid of velocity vectors for the droplets in the plane of the laser sheet can be determined simultaneously.

2.2 Water Distribution

Ten pan tests are conducted using one sprinkler located above a rotating array of pans as shown in Figure 2. Ten pan tests provide a measure of the delivered water density as a function of radial distance from the fire. Test

parameters that are typically changed in pan distribution tests are the height of the sprinklers above the pans and the water flow rate at the sprinkler.

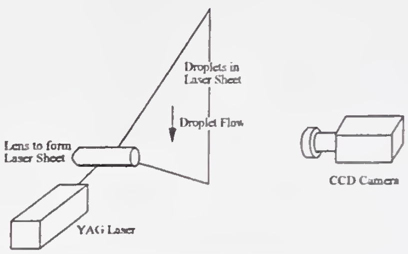

Figure 1. Sketch of PIV setup

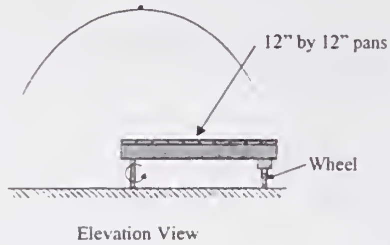

Figure 2. Pan Distribution Tests

3 Analysis Techniques

3.1 Droplet Trajectory

Water from sprinklers ejects from a circular orifice to form a water jet. The water jet impacts against a deflector and disperses in a thin sheet or thin streams called ligaments, which break up into droplets due to surface tension and inertial forces. [1]

The trajectories of the droplets may be analyzed once the stable droplets are formed. Assuming that this happens a short distance away from the deflector and that the droplets are spherical in shape once formed, the trajectory of droplets may be described with the analysis of forces on a sprinkler drop as depicted in Figure 3.

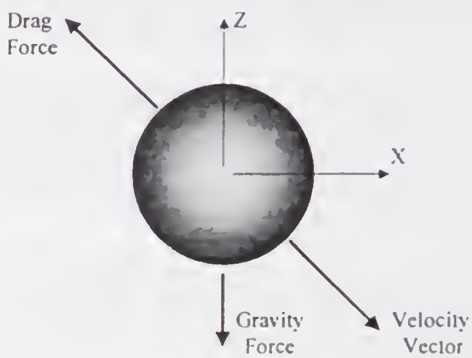

Figure 3 – Forces on a Sprinkler Spray Drop

These forces may be used to describe the force balance as shown in equation (1.1). In this equation, the left hand side represents the change in momentum of the drop. The first term on the right hand side is the force of gravity on the droplet and the second term is the drag force that the surrounding air exerts on the droplet [2].

$$\frac{\partial}{\partial t}\left(m_d \vec{u}_d\right) = m_d \vec{g} - \frac{1}{2}\rho C_d A_d \left(\vec{u}_d - \vec{u}_\infty\right)\left|\vec{u}_d - \vec{u}_\infty\right| \qquad (1.1)$$

Here m_d is the mass of the droplet, g is the acceleration due to gravity, ρ is the density of water, A_d is the projected area of the droplet, C_d is the drag coefficient, u_d is the velocity of the droplet and u_∞ is the velocity of the surrounding air. The quantities g , u_d and u_∞ are vectors.

The drag coefficient, C_d, for spheres can be found in the literature [3] to be a function of the Reynolds Number as shown in equation (1.2).

$$C_d = \frac{24}{\mathrm{Re}} + \frac{6}{1+\sqrt{\mathrm{Re}}} + 0.4 \qquad (1.2)$$

The trajectory of individual droplets was calculated by solving equation (1.1) using a 4th order Runge-Kutta algorithm. The velocity of the ambient air was always assumed to be zero. The initial velocity vector and the droplet diameter were user-defined input variables. The velocity vector was allowed to change in response to the solution of equation (1.1). The droplet size was assumed to remain constant.

3.2 Delivered Water Density Based on Droplets near the Sprinkler

The effectiveness of a sprinkler in controlling a fire depends on the amount of water that the sprinkler can deliver to the fire location. When water spray characteristics are known near the sprinkler, it should be possible to calculate the delivered water density at any location. This calculation is made challenging because of the large number of water droplets and because the droplet sizes, droplet velocities, and water fluxes are different at different angles from the sprinkler.

Because the sprinkler spray is not immediately a fully developed droplet flow (i.e. droplets are still forming and changing shape and size), the measurement of sprinkler spray characteristics must be made at a distance away from the sprinkler. For this reason, the droplet flow has been evaluated by modeling the sprinkler as existing at the center of a spherical region as shown in Figure 4.

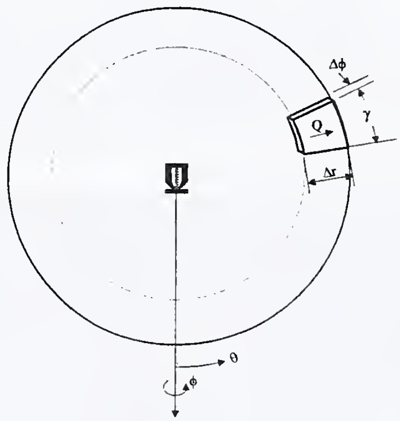

Figure 4. Sprinkler Located at center of Sphere

The experimental measurements are mapped into differential volumes as shown in Figure 4. The velocity, droplet sizes, and water flux are assumed to be uniform within each differential volume and are allowed to have different values in different volumes.

Using the measured droplet sizes and velocities obtained using PIV, the water distribution at a plane below the sprinkler can be calculated as follows. The droplet density in a differential volume is calculated from the area of droplets measured in the PIV images. The measured flow rate in a differential volume, Q, is calculated from the product of the average droplet velocity in a differential volume (from PIV), the differential volume, and the droplet density in the volume. The water flux at any plane below the sprinkler is calculated by distributing the measured flow rate in the differential volume, Q, evenly over the area bounded by the trajectories of the droplets at the boundaries of the pie shaped differential volume in Figure 4. The sum of the contributions of all of the individual differential volumes at a plane below the sprinkler provides the water distribution based on the droplet sizes and velocities near the sprinkler. This result can then be compared to the results for large scale water distribution tests.

Several assumptions used in this analysis should be noted. First, the droplet velocity and water flux are assumed to be functions of elevation angle θ and azimuthal angle ϕ. Second, the droplet spray is assumed to be adequately described in 10 degree increments of θ. It is also assumed that the spray has uniform characteristics for ϕ ranging from 30 to 90 degrees, where 0 degrees is parallel to the frame arms. Third, the droplet size distribution near the sprinkler is assumed to be independent of location. This assumption is clearly invalid due to the effects of the frame

arms and irregularly shaped deflectors. The droplet distribution data was also not measured for the sprinklers used. The droplet distribution is assumed to follow a Rosin-Rammler distribution with an identical median diameter and distribution function for all angles. Finally, we have assumed that the interaction between the droplets does not significantly effect the flow.

4 Results

4.1 Trajectory Analysis

A trajectory analysis was conducted to determine the path of individual droplets ejected from a sprinkler. The purpose of the trajectory analysis was to develop a fundamental understanding of the spray characteristics that were observed in the experimental tests. The trajectories of the droplets were calculated using the procedure outlined in section 3.1.

The analysis consisted of calculating the radial distance from the centerline of the sprinkler that a droplet would reach when it has fallen 3 meters below the sprinkler. Droplet diameters ranged from 50 to 7000 microns, initial droplet velocities ranged from 0 to 20 meters per second, and initial velocity angles, θ, ranged from 60 to 110 degrees.

Results for the case where droplets are ejected horizontally from the sprinkler, $\theta = 90$ degrees, are shown in Figure 5. The figure indicates the size of the droplet that lands at a given radial distance from the sprinkler centerline on a horizontal plane 3 meters below the sprinkler, given a particular initial velocity. For instance, 600 micron droplets with an initial velocity of 2 m/s will land on a plane 3 meters below the sprinkler at about 1 meter from the sprinkler centerline. Data is shown in Figure 5 for initial velocities ranging from 2 to 20 m/s and droplet diameters of 100 to 1200 microns.

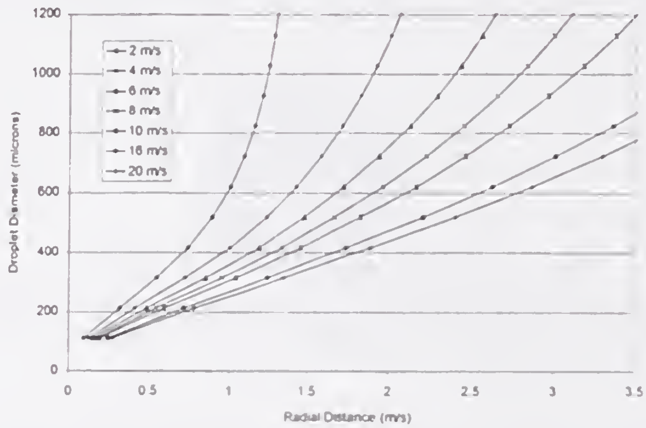

Figure 5. Droplet Size Versus Radial Position (numerical solution)

It is evident that larger droplets travel further radially than smaller droplets regardless of the initial horizontal velocity. At low initial velocities, the difference in the distance that the largest and smallest droplets travel is much less than the difference at larger initial velocities.

The tendency for larger droplets to travel further horizontally than smaller droplets was found for all initial velocities and angles in this study. A similar result was found experimentally by Chan [4] for three ESFR sprinklers. Likewise, Phased Doppler Particle Analyzer measurements at Underwriters Laboratories show the same result.

4.2 Experiments

Experimental results presented here are for a Grinnel Model FR-1 sprinkler with a nominal orifice coefficient of $k=5.5$ gpm/(psi)$^{1/2}$. Experiments were conducted at a nominal flow rate of 57 LPM (15 gpm). Four series of

experiments were conducted with the sprinkler frame arms parallel, 10, 20, and 30 degrees from the PIV laser sheet, corresponding to ϕ=0, 10, 20, and 30 degrees.

In each sprinkler orientation, one hundred PIV image pairs were collected with a 0.3 millisecond interval between each frame of an image pair. Image pairs were taken with a 66 millisecond separation. The resolution of the PIV images was 0.294 mm/pixel in a 1000 by 1000 pixel image for a total image area of 294 by 294 mm (11.6 by 11.6 inches).

Figure 6 shows PIV generated velocity vectors superimposed over the PIV image. The sprinkler is located in the upper left-hand corner of the image. The water jet is clearly visible between the two sprinkler frame-arms. Water ligaments hide the deflector. The image shows that the majority of the water ligaments have broken up into droplets by about 100 mm from the sprinkler. The image clearly shows that the water density is non-uniform with respect to elevation angle θ.

4.3 Droplet Velocities

The radial velocity of the droplets was calculated using the following procedure. The average droplet velocity for each location on a 13 by 13 uniform grid for the 100 image pairs was calculated after first removing any vector that was more than 3 standard deviations from the median in that grid location. The radial and angular components of velocity were calculated using the center of the orifice as the origin and using a linear interpolation to find velocities at locations not on the 13 by 13 grid. The origin was then shifted vertically to find the location with the minimum angular velocity components. This resulted in a virtual origin location between the orifice and the deflector, though closer to the orifice. After locating the virtual origin, the radial velocities were at least 20 times larger than angular velocities except in the regions with small velocity.

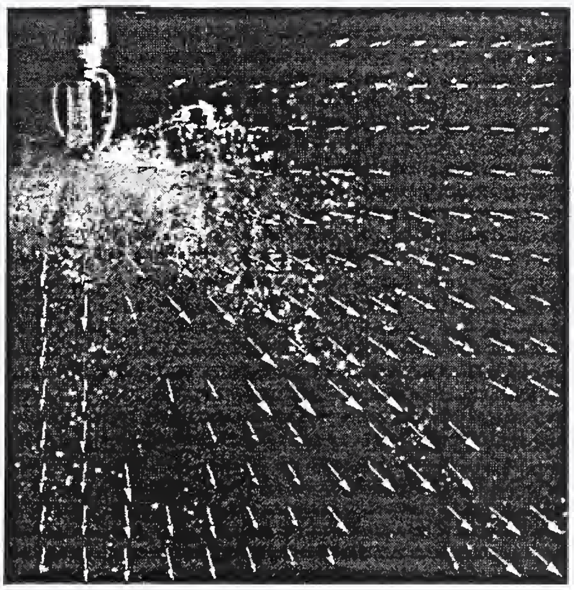

Figure 6. PIV Image

Figure 7 shows the radial velocity on a circle 200 mm from the virtual origin. The radial velocity is plotted on the vertical axis as a function of the elevation angle, θ, from the vertical axis (ranging from 0 directly below the sprinkler to 90 degrees directly to the side of the sprinkler). The droplet velocity ranges from 3.7 to 8.2 m/s. The four series in the Figure represent the four sprinkler azimuthal orientations in the ϕ direction.

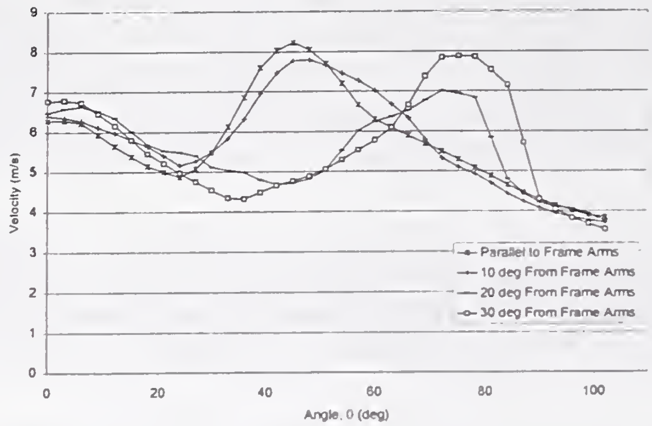

Figure 7. Droplet Radial Velocity at a 200mm Radial Distance from Sprinkler

It is evident that the droplet velocity is a function of both the elevation angle θ and the azimuthal angle ϕ. Figure 7 also shows that the velocities parallel to the frame arms and at 10 degrees from the frame arms are similar one another. Likewise the velocities at 20 and 30 degrees to the frame arms are similar. This suggests that the frame arm effect on the velocity profile dies out between 10 and 20 degrees.

4.4 Water Flux

Figure 8 shows the water flux leaving the sprinkler that was calculated from the PIV images using the procedure outlined in section 3.2. The Figure shows the water flux as a function of the elevation angle, θ, from the vertical axis. The droplet density was calculated in 3 degree wide regions that were bounded by the radial distances of 175mm to 225 mm from the origin. The virtual origin calculated in section 4.3 was used.

Clearly the greatest water flux for this sprinkler is directly below the sprinkler at all azimuthal angles. For planes parallel or nearly parallel to the frame arms, the flux is also highest around 45 degrees. Away from the frame arm, a higher water flux occurs at greater angles. It is important to note that although the water flux is quite large directly below the sprinkler, the effect of this is fairly small when integrated over the spherical region shown in .

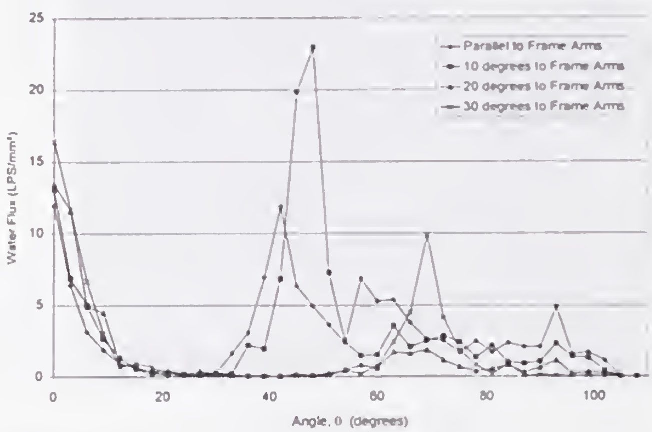

Figure 8. Water Flux

4.5 Delivered Water Density

Figure 9 shows the delivered water density on a plane 3m below the sprinkler that would be calculated if the spray could be treated as an axisymmetric flow. In other words, each chart in Figure 9 shows the calculated water density as if the spray characteristics at each sprinkler angle, ϕ, could be assumed to be characteristic of the entire spray.

Figure 9 demonstrates that the spray characteristics at each sprinkler angle, ϕ, produce different delivered water densities and that the sprinkler sprays can not be characterized as axisymmetric flows.

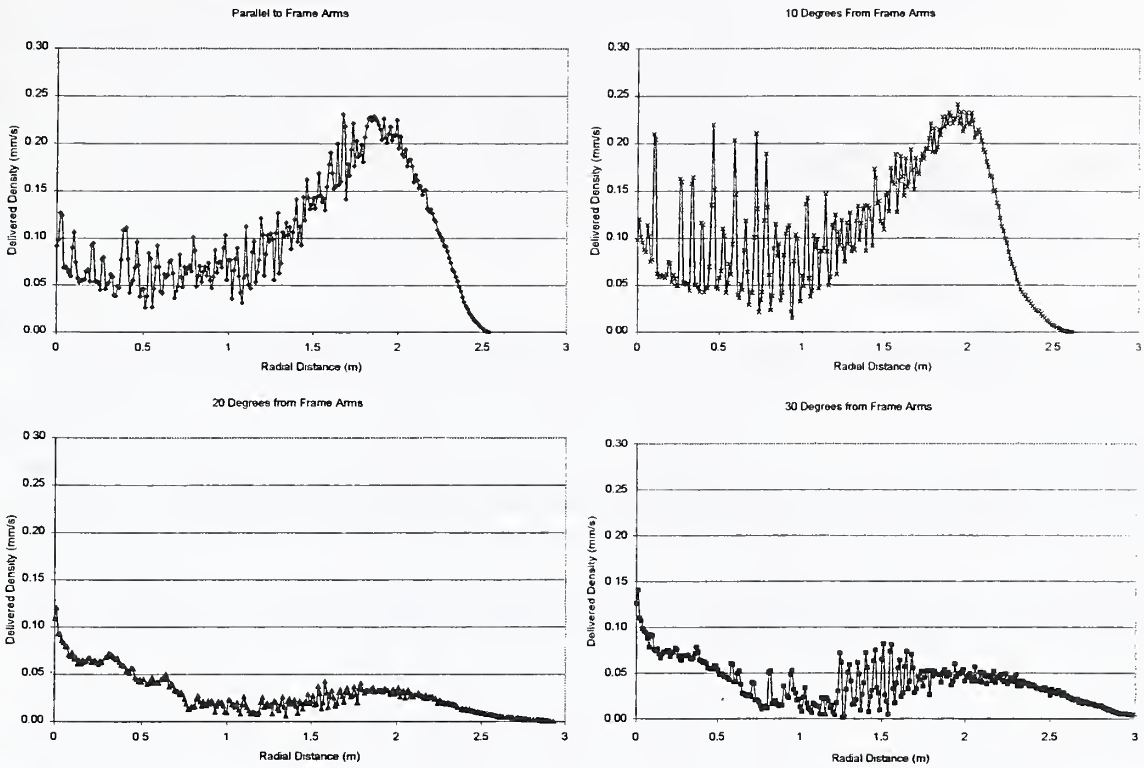

Figure 9. Calculated Delivered Water Density for Each Sprinkler Orientation

The delivered water densities calculated for each sprinkler angle, ϕ, were then combined to produce a composite delivered water density. The spray was assumed to be quadrilaterally-symmetric. That is, the spray in each azimuthal quadrant is assumed to be similar. The delivered density from the experiment parallel to the frame arms was assumed to contribute 5/90 of the delivered density. The delivered density from the experiments 10 and 20 degrees from the frame arms were each assumed to contribute 10/90 of the delivered density. The delivered density from the experiment at 30 degrees from the frame arms was assumed to contribute 65/90 of the delivered density. The resulting delivered water density is shown in Figure 10.

The composite delivered density shows characteristics of each of the individual experiments. The peak below the sprinkler is due to the influence of the experiments at ϕ values of 20 and 30 degrees. The rise that occurs at 2 meters is primarily due to the influence of the experiments at ϕ values of 0 and 10 degrees.

4.6 Comparison with 10-Pan Distribution Data

Figure 11 shows the results of two 10-pan distribution tests. The results show that there is a peak directly below the sprinkler, a minimum at 0.5 m, and another maximum at 1m. Comparison of Figure 10 and Figure 11 shows that the general shape of the curves is similar. The calculated water distribution extends further than the 10-pan data. The water distribution in the pan tests reduces to trace amounts at distances greater than 2.2m, whereas the calculated water distribution does not reduce to trace amounts until 2.8m. The magnitude of the delivered density in both Figures is similar. The magnitude of the data in the calculated water distribution is less due to the larger area the sprays at a larger distance must cover.

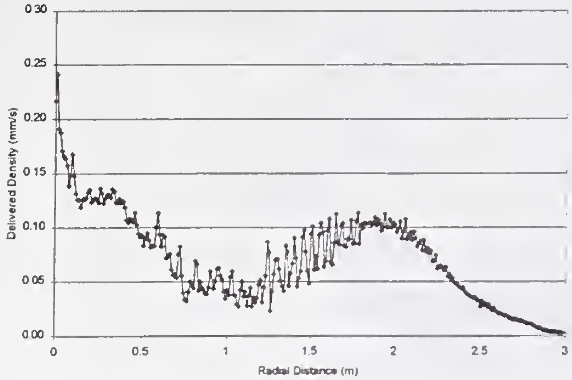

Figure 10. Composite Water Density

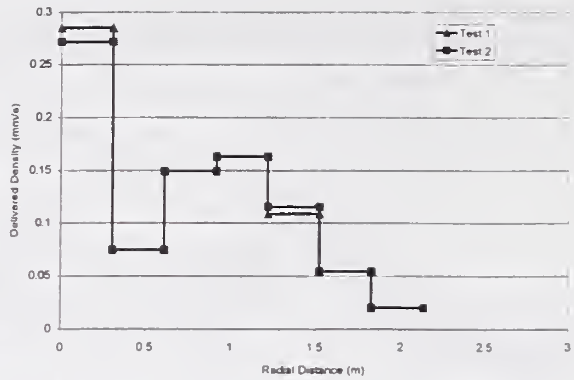

Figure 11. Pan Distribution Results

5 Conclusion

In this paper, an analytical trajectory analysis was combined with Particle Image Velocimetry experiments. The trajectory analysis was used to predict the path of individual droplets. Particle Image Velocimetry (PIV) was used to develop the input parameters at the sprinkler needed for the trajectory analysis.

The trajectory analysis showed that larger droplets always travel farther horizontally from the sprinkler than smaller droplets. This phenomena is caused by the momentum of larger droplets being proportionally larger than the drag force.

The experimental study has shown that the droplet velocities and water fluxes are different at different angles from the sprinkler. For the sprinklers evaluated, it was found that the droplet velocities could be characterized as a purely radial flow at a radial distance of 200 mm. Droplet velocities up to 8.2 m/s were measured from a k=5.5 gpm/(psi)$^{1/2}$ flowing water at 15 gpm.

The combination of the trajectory analysis and the experimental study was used to predict the water density measured in the traditional pan distribution tests. The results of this comparison provided good preliminary results. Further refinement of the analysis and experimental techniques will be required to provide acceptable engineering results.

Acknowledgements

The authors would like to acknowledge the National Institute of Standards and Technology for funding this effort and Underwriters Laboratories for providing the facilities.

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DEVELOPMENT OF RESIDENTIAL SPRINKLERS AND ISSUES HIGHLIGHTED BY RECENT RESEARCH

Hsiang-Cheng Kung
Factory Mutual Research
Norwood, MA 02062

INTRODUCTION

A test program[1] was conducted at Factory Mutual Research from June 1978 to June 1979 to investigate the effects of sprinkler link sensitivity and water distribution characteristic upon sprinkler performance in typical residential fire scenarios. The test results show that sprinkler links that are significantly more sensitive than conventional industrial sprinkler links were essential in providing adequate life-safety and property protection in residential fires. A high-challenge, fast-developing fire scenario was identified. This scenario involved a shielded fire set in the corner of a ventilated living room having plywood paneled walls and a combustible ceiling. One residential sprinkler prototype proved successful in controlling fires in this ventilated living room test scenario. This prototype had a link with a Response Time Index[2] of 48 $(ft * s)^{1/2}$, (26.5 $(m \times s)^{1/2}$) a temperature rating of 140°F (60°C), and distributed adequate water to the walls and corners of the room.

Since sprinkler control of residential fires depends not only on sprinkler operation characteristics, but also on building geometry, ventilation condition and fire loading, the evaluation of sprinkler performance in a different building geometry was highly desirable. To accomplish this, a test program[3] was conducted to evaluate the prototype sprinkler in an actual residential dwelling. A two-story Spanish-stucco house located in Los Angeles, California was used for this purpose.

With data from these two programs, the NFPA 13D Subcommittee prepared a new version of the NFPA 13D Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Mobile Homes.[4] This version was adopted by NFPA in November 1980.

NFPA 13D STANDARD

Since 1980, the NFPA 13D Standard has undergone several cycles of revisions. However, the purpose of the standard has remained unchanged in the last twenty years. "The purpose of this standard is to provide a sprinkler that aids in the detection and control of residential fires and, thus, provides improved protection against injury, life loss and property damage. A sprinkler system designed and installed in accordance with this standard is expected to prevent flashover in the room of fire origin, where sprinklered, and to improve the chance for occupants to escape or be evacuated.[4]"

The standard requires that the system shall provide a discharge of not less than 18 gpm (68 ℓ/min) to any single operating sprinkler and not less than 13 gpm (49 ℓ/min) per sprinkler to the number of design sprinklers. The number of design sprinklers shall include all sprinklers within a compartment up to a maximum of two sprinklers under a smooth horizontal ceiling. The maximum area protected by a single sprinkler does not exceed 144 ft^2 (13.4 m^2). The maximum distance between sprinklers shall not exceed 12 ft (3.7 m) on or between pipelines, and the maximum distance to a wall or partition shall not exceed 6 ft (1.8 m). Furthermore, the minimum distance between sprinklers within a compartment shall be 8 ft (2.4 m).

In Appendix A of the Standard (Explanatory Material), it states that "the criteria in this standard are based on full-scale fire tests of rooms containing typical furnishings found in residential living rooms, kitchens and bedrooms. The furnishings were arranged as typically found in dwelling units in a manner similar to that shown in Figures A-1-1(a), A-1-1(b) and A-1-1(c).[4]" Figure A-1-1(c) represents the living room corner fire scenario used in the 1978-1979 FMRC test program.[1] A schematic drawing of this arrangement is shown in Figure 1.

The standard also permits application rates, design areas and areas of coverage other than those specified to be used with special sprinklers that have been listed for specific residential installation conditions, since it is not the intention of the standard to restrict new technologies or alternative arrangements. However, it is expected that any specific residential sprinklers listed by national recognized laboratories shall prevent flashover in the room of fire origin when they are tested in the living room corner fire scenario shown in Figure 1.

RECENT RESIDENTIAL SPRINKLER FIRE TESTS

Shortly after the adoption of the NFPA 13D 1980 Edition Standard, Underwriters Laboratories (UL) separately developed a fire test for their residential sprinkler standard (UL 1626[5]). The UL test compartment was constructed using combustible paneling and ceiling tiles. The fuel package included a wood crib placed over a pan containing heptane and foam supported by a wood stand, simulating upholstered furniture ends. The UL test arrangement is shown in Figure 2. The fuel package was designed by UL to simulate fire growth and shielding observed in the upholstered chair fire of the Los Angeles Residential Test Program.[3] During the time period since UL 1626 was first issued, UL has used this fire test to list special residential sprinklers over a wide range of spacings and flow rates.[6]

FMRC gained experience with the UL 1626 fuel package during a USFA-sponsored study investigating the feasibility of using water mist systems for residential fire protection.[7] In 1996, FMRC decided to adopt the UL 1626 residential fire test for its Approval Standard of residential sprinklers. In 1999, a series of fire tests was conducted to evaluate the reproducibility of fire test results utilizing the UL 1626 Residential Fire Test Standard. In response to UL's submittal of this standard for ANSI's recognition, five different models of UL listed residential sprinklers were evaluated at their respective listed discharge rates, one of which was the Grinnell F954

model (Model H in Table 1), which is representative of the prototype model used in the Los Angeles Residential Test Program. For all sprinkler models except Model F954, fire tests were conducted in an enclosure 16 ft wide, 32 ft long and 8 ft high as specified in UL 1626 for residential sprinklers installed on 16 ft spacing. For the F954 Model, a 12 ft wide, 24 ft long and 8 ft enclosure was used.

In all the tests of UL listed models at their respective listed discharge rates, only the F954 Model met the criteria for acceptability as specified in UL 1626. In all the other tests, a third sprinkler installed in the doorway actuated. In three of the tests, the tests were aborted less than two minutes after ignition of the wood cribs due to excess ceiling gas temperatures over ignition and observation of flames propagating across the ceiling and out the doorway closest to the fuel package. These conditions were judged to be indicative of imminent flashover. Results of the fire tests are presented in Table 1.

The Model A residential sprinkler was also tested using the living room corner fuel package shown in Figure 1. This test was conducted in the 16 ft x 32 ft x 8 ft high (4.88 m x 9.76 m x 2.44 m high) enclosure. Gas temperature and ceiling surface temperature over ignition and gas temperature at 5 ft (1.53 m) elevation at the room center are shown in Figure 3. Ceiling gas temperatures 3 in. below the ceiling at several locations are shown in Figure 4. After actuation of the sprinkler closest to the fire, the fire continued to grow and the gas temperature over ignition reached 1600°F (870°C). The second and the third sprinklers actuated 68 and 91 seconds, respectively, after first sprinkler actuation. Flames spread across the ceiling and out of the doorway farthest from the fuel package. Ceiling gas temperatures at the center of the ceiling reached 1000°F (540°C). Gas temperature at 5 ft elevation at the room center reached 220°F (100°C) at 1 minute 50 seconds after first sprinkler actuation. Large sections of the plywood panels in the room corner ignited and burned intensely. At 2 minutes after first sprinkler actuation, the test was aborted.

CONCLUSIONS

1. The fire test criteria of UL 1626 were not met in all tests conducted at listed densities equal or less than 0.055 gpm/ft^2 (2.2 ℓ/min/m^2) at first sprinkler operation.

2. One sprinkler, listed by Underwriters Laboratories for operation at 0.039 gpm/ft^2 (1.6 ℓ/min/m^2) for a single sprinkler discharge and 0.031 gpm/ft^2 (1.3 ℓ/min/m^2) for a two-sprinkler discharge, failed to prevent flashover in a 16 ft x 32 ft x 8 ft high (4.88 m x 9.76 m x 2.44 m high) compartment containing the FMRC living room corner fuel package.

3. A residential sprinkler fire test for listing of residential sprinklers should present a fire challenge comparable to that of the FMRC and the Los Angeles living room corner fire scenarios. The fuel package for the fire tests should consist of commercially available materials, which will have consistent flammability characteristics and be readily available through specification of chemical composition and means of manufacturing so that repeatability of the test can be achieved. As a result of the recent residential sprinkler test

program, UL and FMR have participated in a cooperative effort to develop such a fuel package during the last twelve months.

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Figure A-1-1(c) Living room.

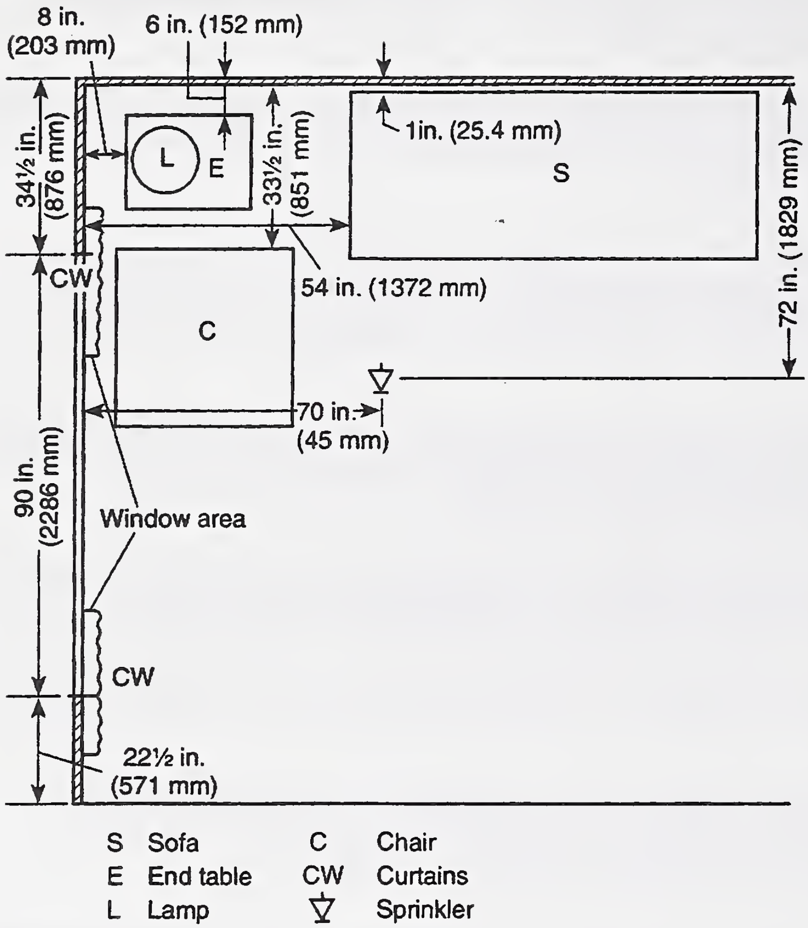

Figure 1. Living Room Corner Fire Scenario.

Figure 26.1
Fire test arrangement – pendent or upright sprinklers

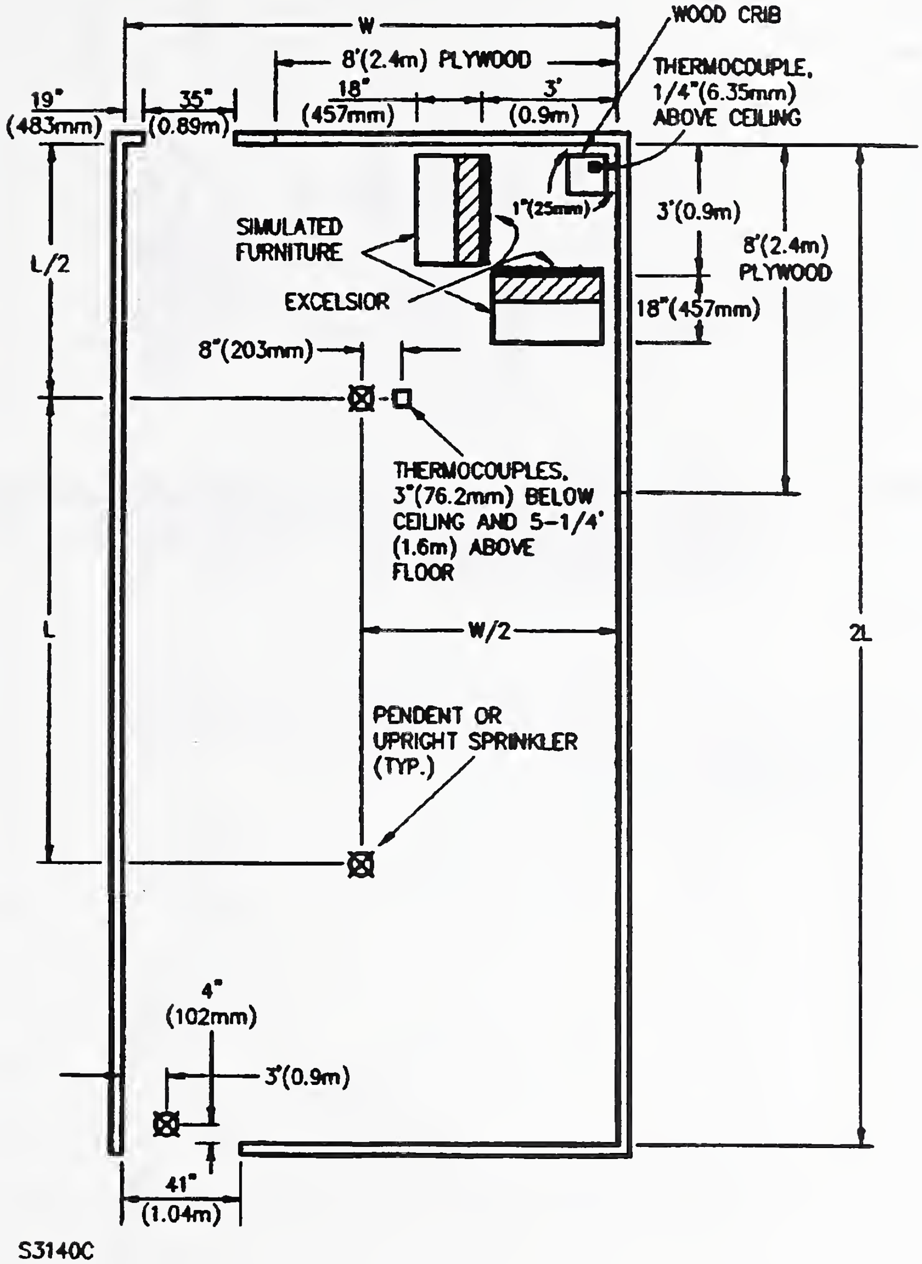

Figure 2. Schematic of UL 1626 Fire Test Setup (Reference 4).

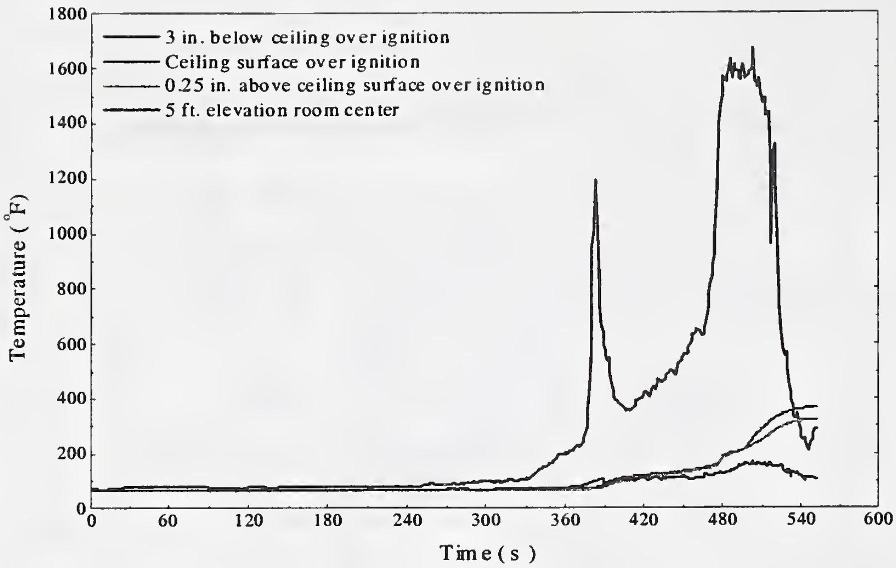

Figure 3. Temperatures over Ignition and at 5 ft in the Center of the Room.
Model A at Listed Density, 0.039/0.031 gpm/ft^2, NFPA 13D Package in 16 ft x 32 ft x 8 ft High Room.

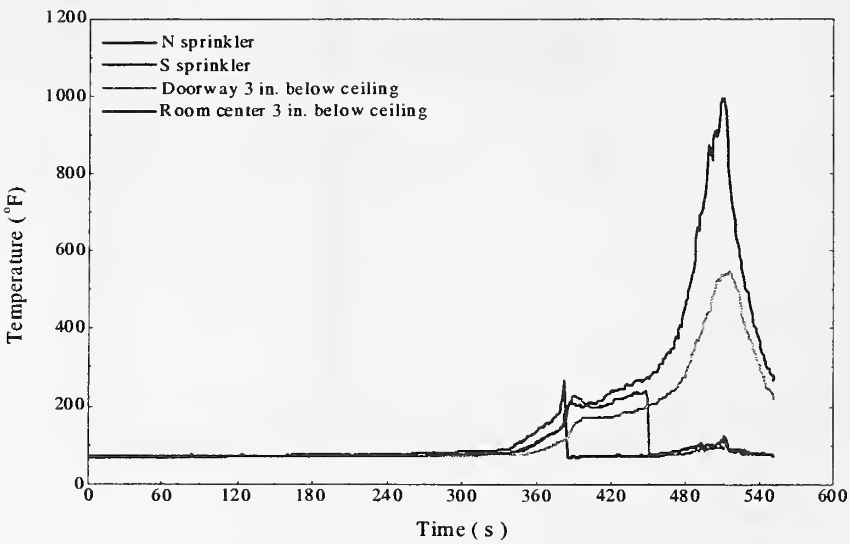

Figure 4. Gas Temperatures 3 in. below Ceiling.
Model A at Listed Density, 0.039/0.031 gpm/ft^2, NFPA 13 D Package in 16 ft x 32 ft x 8 ft High Room.

Table 1. Factory Mutual Test Results Using UL 1626 Package

Sprinkler Model	Listing	K-Factor gpm/psi$^{0.5}$	Temp. Rating (^{o} F)	One/Two Sprinkler Total Flow (gpm)	Density for One/Two Sprinklers (gpm/ft^2)	Test Results When Tested with UL 1626 Test Package
A	UL	3.0	155	10/16	0.039/0.031	Test Failed / Flashover
B	UL	3.0	155	10/16	0.039/0.031	Test Failed / Flashover
C	UL	3.9	155	12/21	0.047/0.041	Test Failed / Flashover
D	UL	4.2	162	14/28	0.055/0.055	Test Failed / 3rd sprinkler operated
H	UL	2.8	165	18/26	0.125/0.09	Test Passed

Development of Pneumatic Atomizing Gun for Fire Fighting

S.Noguchi, S.Okubo and M.Miyasaka
Mitsubishi Heavy Industries, Ltd.
Technical Headquarters Yokohama Research and Development Center
12, Nishiki-cho, Nakak-ku, Yokohama, 231-8715, JAPAN

Abstract

During indoor fire fighting in multiple dwelling houses, water damage (breaking of furniture, etc. and leakage to the first floor by excess water) is a significant problem. Therefore, we are developing the Pneumatic Atomizing Gun (PAG) for Fire Fighting which can reduce the required water quantity. This method atomizes water and air at the same time. Because water is atomized using a high-speed air flow, the particle diameter of drops of water is fine, and at the same time, range of the particles can be raised. As a result of the comparison test to confirm the fire fighting capacity, equal flames were extinguished by a water quantity about 1/6 of that from the existing project gun. It was assumed that fire fighting using a small quantity of water contributed by increasing the heat exchange efficiency due to the fineness of the water particles, and at the same time, satisfying the improvement in efficiency by reaching the origin of the fire using water particles which were not easily fanned by the flames.

Background

Water damage (breaking of indoor furniture, etc., and leakage to the first floor by excess water) to houses has becomes a great problem for indoor fire fighting in multiple dwelling homes and office buildings. At present, the Impulse Gun, Project Gun (Fog Gun), etc. which use a small quantity of water for projecting against water damage are used. However, the former cannot continuously spray water and the latter requires a high water pressure and the use of those guns is limited due to insufficient water pressure during fire fighting in multiple floors. Each gun has certain faults (Table 1). Also, there are potential problems that the fine drops of water are difficult to reach the origin of a fire.

On the other hand, PAG, which is used as a snow gun, etc., of an artificial snowfall machine, can continuously atomize water at low pressure and can overcome the fault of the existing water-saving type nozzle. The direct spraying of fine water particles is extremely superior to that of a nozzle atomizing only water. By using this for fire fighting, a great effect can be expected for preventing water damage. Therefore,

the fire fighting test was performed in order to confirm the fire fighting capacity and them compared with the existing water-saving type nozzle.

Table 1. Comparison of water-saving type fire fighting nozzle

	Structure	Continuously spouting water	Atomizing at low water pressure*
Inpluse Gun	Spouting water by high pressure air	×	○
Project Gun (Fog gun)	Atomizing water by high pressure	○	×
PAG	Atomizing water and air at the same time	○	○

*···About 500kPa taking in account fire fighting, etc., at high altitude.

PAG for Fire Fighting

PAG is a gun atomizing liquid and air at the same time. In the nozzle section inlets of liquid and air are separately installed. After the liquid and air are mixed in the nozzle body, both are sprayed from the injection nozzle. PAG has in general the following features.

- Atomizing is possible at low pressure. Since PAG atomizes a liquid by using a high-speed air flow, it can atomize drops into liquid of fine particles at a relatively low pressure.
- Particles have highly direct flow···Since drops of liquid are injected into the air flow, the speed is difficult to be reduced and a direct spray is quite excellent compared with atomization of the liquid only.

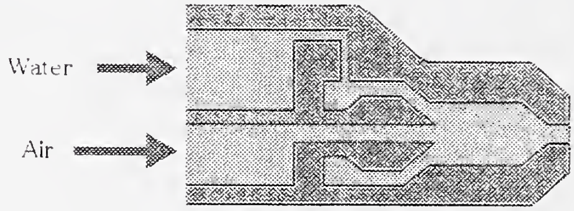

Fig. 1 Concept of PAG

The PAG having those features is considered to be quite suitable for fire fighting using a small quantity of water for the following reasons.

- The conventional project gun (fog gun) is used at 1～1.5MPa and the problem is that the usual pump vehicle and the working pressure for fire fighting at high altitudes cannot be obtained, but PAG can be used at a low pressure of about 500kPa.

• When particle diameter of water is made fine, the heat exchange efficiency of the flame and water is improved and fire fighting with a smaller water quantity may be possible. However, fine water particles, in general, are easily fanned by flames and the amount reaching the origin of a fire is low. However, since the direct spraying of particles from a PAG is excellent, even fine drops of water has a high coefficient of reaching the origin of a fire. At the same time, PAG can satisfy fine drops of water and improving the coefficient reaching the origin of a fire which are two opposite requirements.

To confirm the capacity of the PAG as a water damage prevention-type fire nozzle, the fire fighting test was performed.

Test Goal

The goal of this test is to confirm the fire fighting capacity of the PAG and compare it with the conventional water-saving nozzle. Therefore, fire from the same burning models are actually extinguished using the Project Gun and PAG, and the fire fighting status was observed. Burning models woods were used assuming an indoor fire (combustibles are furniture, interior, etc.) in multiple dwelling houses. The test procedure is as follows.

(1) Burning models are installed in a dummy house. The burning models are constructed of wood above the burning bases in which 2 liters each of gasoline and kerosene are included.

(2) 5 minutes after starting the models on fire, the fighting is started. At this time the fuel was burnt and only the wood was burning.

(3) The Project Gun and PAG extinguish the fire from the same position. The directions of the spouting water were varied up and down, left and right and water was sprayed from all angles on the burning models. Tests included 1 case of the Project Gun ···184 (l/min.) and 4 cases of the PAG ··· 20, 30, 40, 60(l/min.)-5 cases in total were performed.

(4) At the time when the burning models have no flame, the fire fighting was finished. When no flames were found, it was recognized that the fire fighting had finished. When flames are found, water is sprayed until flames cannot be found.

The measured items are water flow rate and the time required for fire fighting. In the PAG, the air flow rate is also measured. The state of flame and fire fighting status are separately observed.

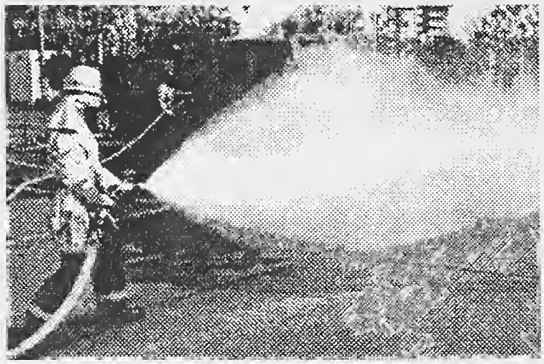

Fig. 2 Project Gun

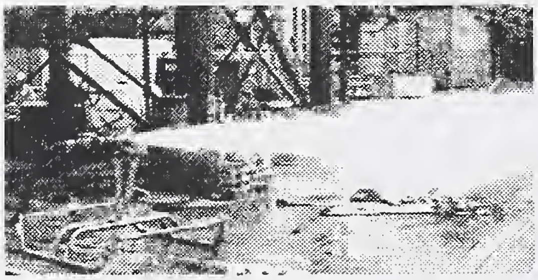

Fig. 3 PAG (under development)

Fig. 4 Burning model

Test Results

In this test, both guns spray water from a fixed point so that the test conditions are the same. Therefore, it takes somewhat longer time to completely extinguish a fire in a blind spot of the burning models although fire in a blind spot can be usually extinguished by going around the blind spot. However, when it is included into the test results, this may be causes of increasing of the experimental error and is not adequate. Therefore, in this test, completion of the fire fighting is specified to be the time when the flames of the burning models cannot be found, and the time and water quantity required for the above status are then recorded.

Table 2 shows the test results. It could be confirmed based on the test results that the PAG can properly extinguish a fire. Furthermore, it was suggested that the optimum value of fire fighting water quantity existed at about 40 (l/min). A future investigation is required to evaluate the influence of the burning models and the air and water ratio.

Next the time and water quantity required for fire fighting using the Project Gun (case 1) and PAG (case 4) were compared (Fig. 5). From the comparison, it became clear that when the PAG was used for fire fighting, the water quantity required for fire fighting was overwhelmingly less and was about 1/6 that of the Project Gun, and the

PAG was effective as a water damage prevention nozzle. The time required for fire fighting is also reduced. The following factors have influence on these results

- When PAG is used, water particles can be atomized and the heat exchange efficiency at the origin of a fire is high.
- Because the force of the water particles is strong and surely reach the origin of a fire. The fire fighting efficiency is high.
- Because the force of the air and liquid mixed flow is strong, blowing out is also effective.

Table 2. Fire Fighting Test Results

case	Gun	Water quantity Qw (l/min)	Air quantity Qa (Nl/min)	Qa/Qw	Required for fire fighting: Time (sec)	Required for fire fighting: Water quantity (l)	Fire fighting status
1	Project Gun	184	–	–	55	169	Fire fighting is possible.
2	PAG	21	1740	82.9	–	–	Fire fighting is impossible.
3	PAG	30	1280	42.7	112	56	It took a significant time to extinguish a fire in a blind spot.
4	PAG	40	950	23.8	40	27	Fire fighting is possible. Blowing out is highly effective.It is required to go around to a blind spot.
5	PAG	60	500	8.3	43	43	Fire fighting is possible, but there is no remarkable superiority compared with 40(l min)

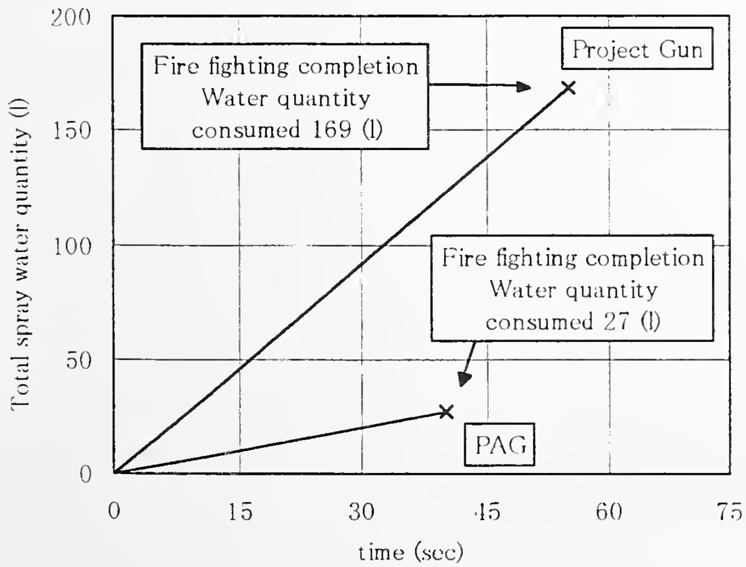

Fig. 5 Comparison of fire fighting status between Project Gun and PAG

Conclusion and Future Development

The fire fighting test was conducted using the PAG in which a reduction of water damage was expected when fire fighting indoor fires. The PAG was compared with the existing water damage prevention nozzle. As a result, it was clarified that when the PAG was used for fire fighting, the water quantity required for fire fighting was about 1/6 that of the Project Gun and was overwhelmingly less. The time required for fire fighting was also reduced and the outlook for putting this system to practical use was obtained. It is expected that a detailed study of the compressor section, hoses conveying the water and air that are loaded on a fire engine and the gun structure will be made for putting this system into practical use, and development of the PAG for fire fighting is completed.

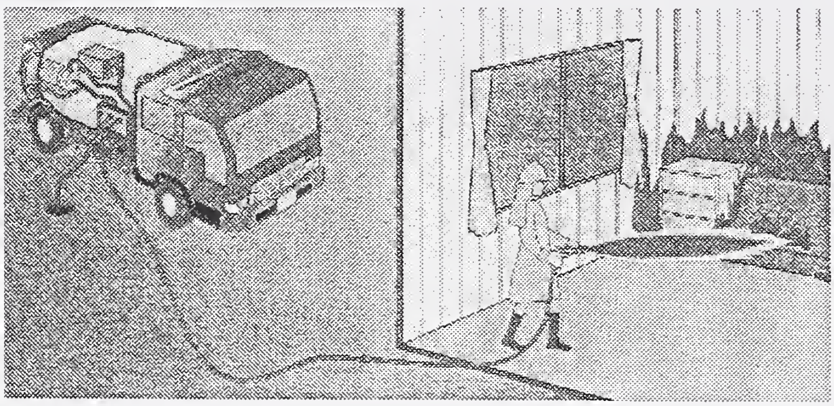

Fig. 6 PAG for Fire Fighting and Concept of System

Reference

[1] Japanese Association of Fire Science and Engineering: Fire Handbook (3rd Edition), Kyoritsu Shuppan 1985